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Lidar Performance Analysis

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Introduction

This report details work carried out under NASA contract NAS8-38609.

Section 1 details the theory used to build the lidar model, provides results of using the model to evaluate AEOLUS design instrument designs and provides snapshots of the visual appearance of the coded model.

Appendix A contains a Fortran program to calculate various forms of the refractive index structure function. This program was used to determine the refractive index structure function used in the main lidar simulation code.

Appendix B contains a memo on the optimisation of the lidar telescope geometry for a line-scan geometry.

Appendix C contains the code for the main lidar simulation and brief instructions on running the code.

Appendix D Contains a Fortran code to calculate the maximum permissible exposure for the eye from the ANSI Z136.1-1992 eye safety standards.

Appendix E contains a paper on the eye safety analysis of a space-based coherent lidar presented at the 7th. Coherent Laser Radar Applications and Technology Conference, Paris, France, 19th-23rd July 1993.

1.0 The lidar model

1.1 Description

The coherent lidar model was developed to allow the assessment of various space-based coherent Doppler lidar instruments under consideration at NASA Marshall Space Flight Center as part of the Laser Atmospheric Wind Sounder (LAWS) program. This section describes the theory used in the model.

1.1.1 Principle of operation

A Doppler lidar wind sounder measures the wind velocity at a remote location. It does this by transmitting an optical pulse which has a narrow frequency spread. This optical pulse is backscattered from aerosol targets (for the optical frequencies under consideration here) in the atmosphere. These aerosol particles are moving with the velocity of the local wind field and therefore impart a Doppler shift to the backscattered light. The backscattered light is collected at the lidar receiver and mixed with an optical local oscillator to produce a heterodyne beat signal on a detector. This heterodyne frequency (less any offset between the LO and transmitter laser) is proportional to the velocity difference between the lidar and the aerosol target. For a stationary lidar this difference is due solely to the aerosol velocity along the line of sight of the lidar. For a moving lidar, the lidar velocity along the line of sight of the instrument must be removed to obtain the aerosol velocity.

1.2 Lidar geometry

Figure (1.1) shows the geometry for a coherent lidar at an altitude, h above a spherical earth of radius, R_e . The line of sight of the instrument makes an angle, θ_n , called the nadir angle with the vertical from the earth to the lidar. The nadir angle at the surface is θ_{ns} , and is given by:-

$$\theta_{ns} = \arcsin\left(\frac{R1}{R_e}\right) \quad (1.1)$$

where $R1$ is the length of the perpendicular from the line of sight to the earth's center and is given by:-

$$R1 = H \sin(\theta_n) \quad \text{where} \quad H = R_e + h \quad (1.2)$$

The range from the lidar to the surface is given by:-

$$R = (H^2 + R_e^2 - 2HR_e \cos(\theta_{ns} - \theta_n))^{0.5} \quad (1.3)$$

For a target at an arbitrary altitude, z above the earth's surface, the nadir angle at the target and range from the lidar are given by substituting $(R_e + z)$ for R_e in equations (1.1) and (1.3) respectively, i.e

$$\theta_n(z) = \text{asin}\left(\frac{R1}{R_e + z}\right) \quad (1.4)$$

$$R(z) = (H^2 + (R_e + z)^2 - 2H(R_e + z) \cos(\theta_{nz} - \theta_n))^{0.5} \quad (1.5)$$

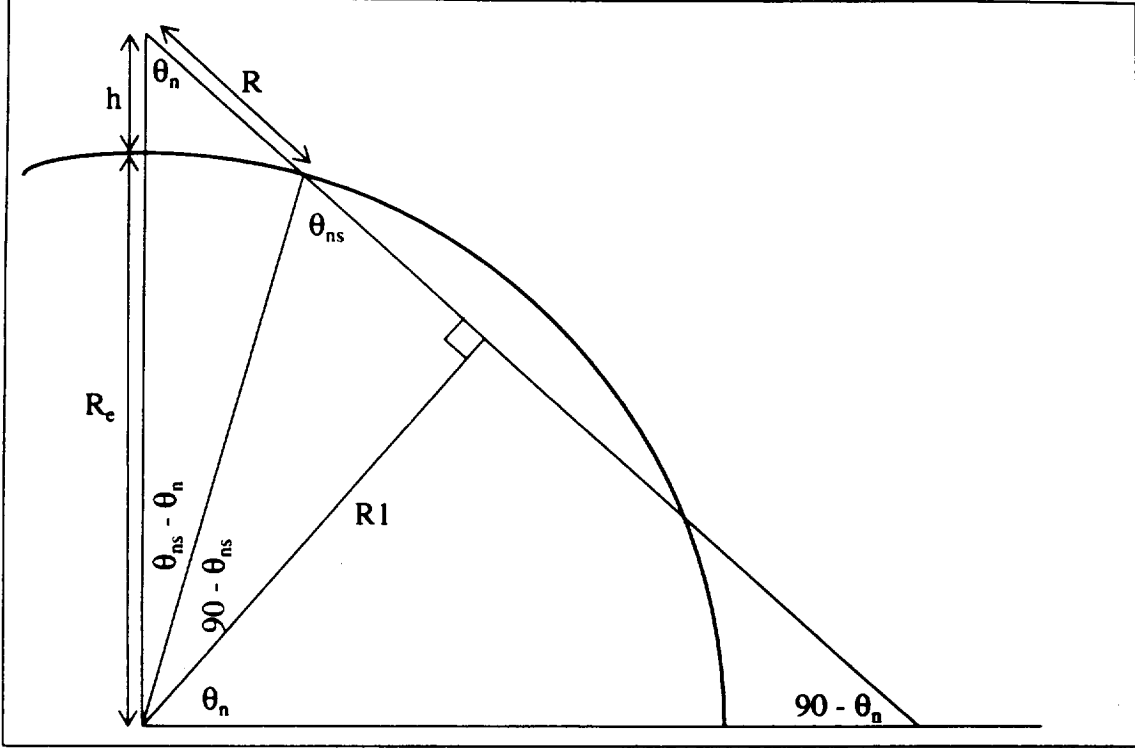


Figure (1.1) The geometry for a space-based lidar.

1.3 The coherent lidar signal to noise ratio equation

For an aerosol target at range, R with uniform backscatter coefficient, β over the dimensions of the transmitted beam, detector noise dominated by Local Oscillator (LO) shot noise the Coherent Laser Radar (CLR) SNR is given by:

$$\text{SNR} = \frac{U_L T_T T_{TAR} T_A^2 \beta \pi D^2 T_{RAR} \eta c}{8 h \nu B R^2 \left[1 + \frac{\pi D^2 \eta_{mix}}{2 T_R \rho_0^2} \right]} \quad (1.6)$$

where U_L is the laser energy, T_T is the intensity transmittance of the transmit optics due to aperturing and obscuration, T_{TAR} is the intensity transmittance of the transmit optics due to losses (absorption, reflection) that are independent of the beam cross-section position, T_A is the one-way atmospheric attenuation, D is the effective diameter of the transmit telescope, T_{RAR} is the intensity transmittance of the receive optics, c is the speed of light in a homogeneous atmosphere, h is Plancks constant, ν is the laser frequency, B is the signal bandwidth of the detector, η_{mix} (some-

times referred to as η_h) is the CLR mixing efficiency assuming perfect alignment and perfect polarisation matching, T_R is the intensity transmittance of the transmit optics due to aperturing and obscuration, ρ_0 is the transverse coherence length of the backscattered optical field at the CLR, and η is given by:

$$\eta = \eta_{\text{mix}} \eta_A \eta_P \eta_{\text{HQE}} \quad (1.7)$$

where η_A is the change in mixing efficiency due to misalignment between the back propagated local oscillator (BPLO) and the signal beam, η_P is the BPLO/signal beam polarisation mismatch factor and η_{HQE} is the detector heterodyne quantum efficiency. The transverse coherence length of the backscattered optical field is given by:

$$\rho_0(R) = \left[Hk^2 \int_0^R C_n^2(x) \left(1 - \frac{x}{R}\right)^{5/3} dx \right]^{-3/5} \quad (1.8)$$

where $H=2.914383$, $k=2\pi/\lambda$ (λ is the optical wavelength) and $C_n^2(x)$ is the refractive index structure constant at range x from the CLR.

1.3.1 Transmitted pulse energy

The term $U_L T_T T_{\text{TAR}}$ represents the energy transmitted by the lidar system. The loss mechanism due to the optics has been split into the two terms T_T and T_{TAR} to allow various lidar geometries to be considered. T_{TAR} is simply the product of the intensity transmission efficiencies of the individual optical components in the transmit path. T_T is more complex and its value is dependent on the geometry of the lidar. Various authors [1-4] have shown that different receiver geometries and aperture truncations of the lidar transmit/receive beams will vary the heterodyne efficiency of the lidar system. Rye and Frehlich [3] analysed the optimum aperture truncation required for three lidar geometries. A summary of their results for Gaussian beams and large detector sizes (no detector aperturing effects) is presented in Table (1.1).

Table (1.1) Optimum Lidar Geometry Parameters

Geometry	Transmitter		Receiver		Mixing Efficiency	System-Antenna Efficiency
	r_{trunc}	T_T	r_{trunc}	T_R	η_{mix}	η_s
Wang [2]	1.763	0.955	1.763	0.955	0.42	0.401
Rye 1[1]	1.626	0.929	1.626	0.929	0.457	0.424
Rye 2[1]	1.736	0.951	1.192	0.758	0.461	0.438

For a given physical diameter, D the $1/e^2$ spot size, σ is related to the truncation radius, r_{trunc} by

$$\sigma = \frac{D}{r_{\text{trunc}} \sqrt{2}} \quad (1.9)$$

and T_T is given by:-

$$T_T = 1 - e^{-\left(\frac{D}{2\sigma}\right)^2} \quad (1.10)$$

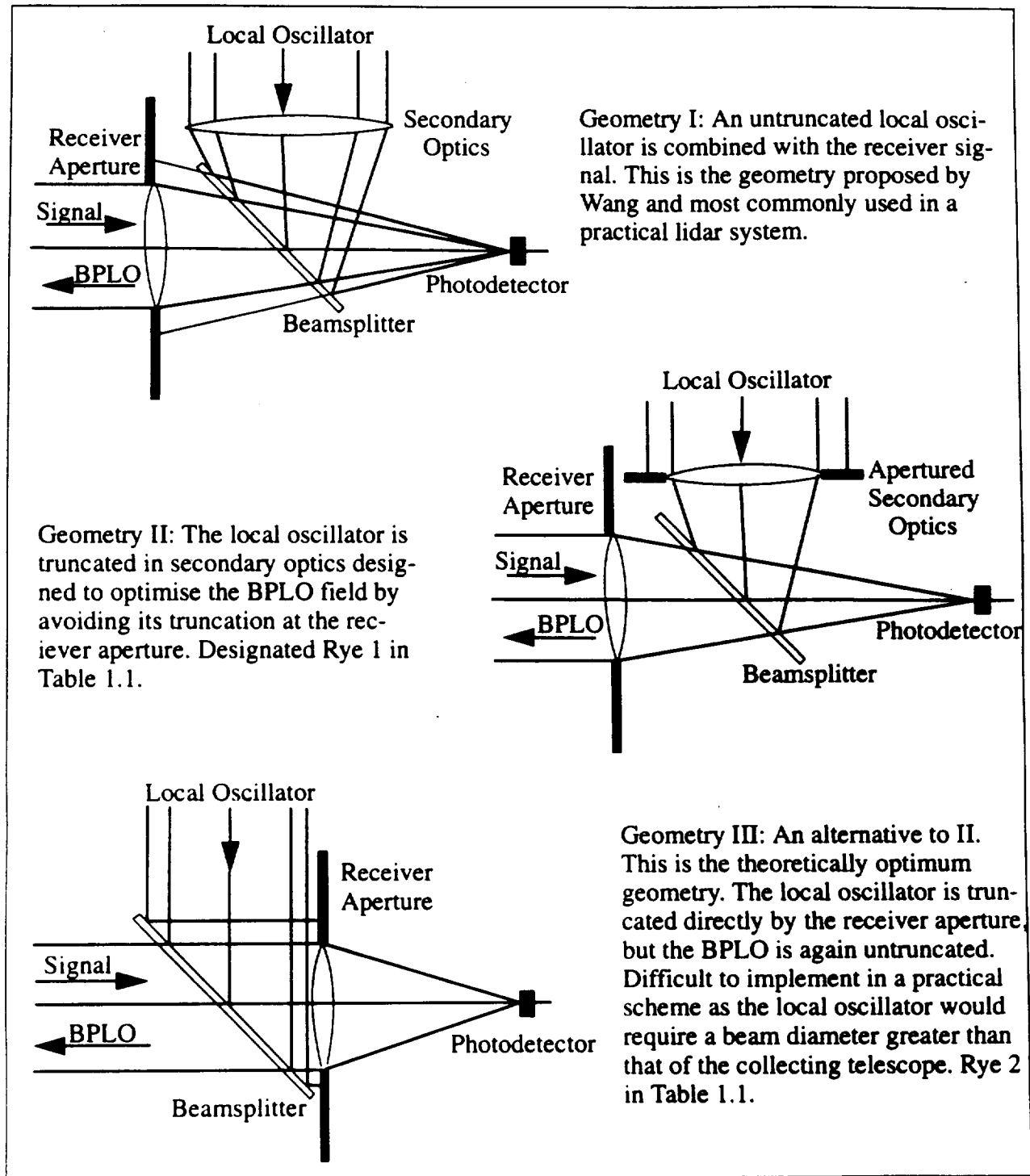


Figure (1.2) The three receiver geometries discussed by Rye and Fröhlich[3].

The system-antenna efficiency, η_s is given by:-

$$\eta_s = \eta_{\text{mix}} \frac{A_R}{A_T} T_T \quad (1.11)$$

where A_R and A_T are receiver and transmitter aperture areas respectively. The lidars under consideration here (monostatic lidars) have a common transmit/receive aperture and therefore $A_R=A_T$ and the system-antenna efficiency is simply:-

$$\eta_s = \eta_{\text{mix}} T_T \quad (1.12)$$

1.3.2 Atmospheric attenuation

Atmospheric attenuation of the lidar beam arises from molecular and aerosol absorption and scattering. The Air Force Geophysical Laboratory has an atmospheric transmission/attenuation model based on the Hitran molecular database. This model or an equivalent can be used to generate atmospheric extinction/km as a function of altitude for each of the wavelengths of interest. The lidar model developed here uses these extinction as a function of height profiles to calculate the extinction between the lidar and the target aerosol. The model divides the atmosphere into 0.1 km thick layers from 0 km to 20 km. Above 20 km the extinction is insignificant and can be ignored for the purposes of this model. The atmospheric extinction, T_A from the lidar to a target in the atmosphere is then given by:-

$$T_A = e^{-\sum \alpha_n l_n} \quad (1.13)$$

where n is the number of atmospheric layers from 20 km down to the target, α_n and l_n are the extinction coefficient and path length respectively for layer n . The path length, l_n in a layer between altitudes z_1 and z_2 is simply:-

$$l_n = R(z_2) - R(z_1) \quad (1.14)$$

where $R(z)$ is given by equation (1.5).

1.3.3 The refractive index structure function.

The WPL-37 refractive index profile [5] is an experimental refractive index structure function profile which has been used in lidar modeling [6]. It can be approximated using:

$$C_n^2(z) = \begin{cases} 0 & z > 20\text{km} \\ 3.66 \times 10^{-17} & 20\text{km} > z > 3\text{km} \\ 1.59 \times 10^{-12} \times z(m)^{-4/3} & 3\text{km} > z > 10\text{m} \\ 7.36 \times 10^{-14} & 10\text{m} > z \end{cases} \quad \text{for} \quad \text{respectively} \quad (1.15)$$

Fairall and Frisch of NOAA have developed an analytic model of the refractive index structure function which takes into account location, season and local conditions[7]. This is an extensive model and the reader is referred to their technical memorandum for details, however the following topographical corrections were mentioned by the authors and should be noted:

Equations 19 and 24c on pages 7 and 8 of reference [7] should read:

$$L = T / (\kappa g) (u_*^2 T_*)$$

and:

$$h_t(\xi) = 10 (1 - \xi)^{-3/2} (2 - \xi)^{-1}$$

respectively and Table 1 of reference [7] should be altered and added to as follows:-

	Colorado				Florida			
	Winter		Summer		Winter		Summer	
	Day	Night	Day	Night	Day	Night	Day	Night
β_o	1	10	2	10	0.35	10	0.25	10
α	0.4	0.9	0.2	0.9	0.2	0.9	0.2	0.9
u_*	0.5	0.1	0.35	0.1	0.5	0.1	0.35	0.1
$R_{net} (Wm^{-2})$	300	-100	600	-100	350	-100	700	-100
z_i (m)	1200	100	2000	100	2000	100	2000	100
z_t (m)	7000	7000	12000	12000	9000	9000	14000	14000
T_0 (K)	278	263	298	288	288	283	303	293

Table (2.2) Parameters for the Fairall and Frisch C_n^2 model.

Additionally the refractive index structure function for the atmosphere of the ocean trade winds (e.g. off Florida) can be calculated using the Florida summer day parameters with α , changed to 0.93.

Fortran code to generate the experimental WPL-37 C_n^2 profile and the Fairall and Frisch models was developed (See "Appendix A - Refractive Index Structure Function Calculation" on page 23.). Appendix A also includes plots of these profiles. It can be seen that the model profiles and the WPL-37 profile are in general agreement. For the purposes of the lidar analyses under consideration here, variations in the refractive index structure function have small effects on the lidar SNR and so it was decided that the model would use the WPL-37 profile as a generic profile.

1.4 The efficiency term

This consists of the four terms η_{mix} , η_A , η_P and η_{HQE} . The mixing efficiency (assuming perfect alignment), η_{mix} is geometry dependant and is given in Table (1.1). The variation of the mixing efficiency as a function of the misalignment angle [9] between the BPLO and signal beams is shown in Figure (1.3), where D is the telescope diameter and λ is the optical wavelength.

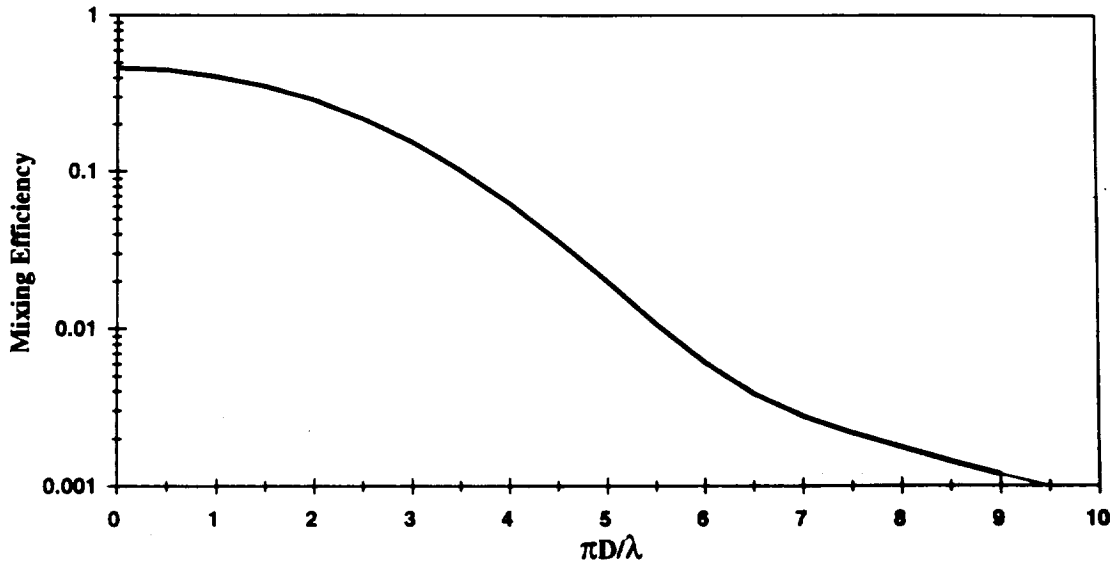


Figure (1.3) Mixing efficiency as a function of $\pi D / \lambda$.

As has been indicated previously the maximum mixing efficiency is dependant on the geometry used and so for the purposes of the lidar model the alignment efficiency, η_A was obtained by normalising the data used to plot Figure (1.3) by dividing by the maximum mixing efficiency. The mixing efficiency for a system with misalignment is then given by taking the mixing efficiency due to geometry considerations (Table (1.1)) and multiplying by η_A .

The values of atmospheric backscatter, β typically used are based on experimental field results using an assortment of lidars with assorted polarisation states. It may therefore be assumed that losses due to polarisation are explicitly accounted for in the use of experimentally derived β values and therefore additional losses due to polarisation are likely to be small. However for completeness, the polarisation efficiency, η_P , although set to unity, is included in the model formulation.

The detector heterodyne quantum efficiency, η_{HQE} is the efficiency with which the detector converts coherent photons into photoelectrons at the maximum bandwidth of the signal. For a detector on a spacecraft orbiting at ~ 7 km/s this corresponds to a bandwidth of ~ 1.4 GHz at $9 \mu\text{m}$ and ~ 12 GHz at $2 \mu\text{m}$. The heterodyne quantum efficiency is usually significantly smaller than the DC quantum efficiency.

1.5 The velocity estimator

The model uses a parameterised maximum likelihood estimator[10] provided by Dr. Rod Frehlich. The model provides values of the standard deviation of good estimates, g and the fraction of bad estimates, b as functions of Φ , the effective number of photo-electrons detected for fixed values of M , the number of samples and Ω , the effective number of independent samples per estimate. The values of these parameters are given in Table (3.3). The variation of g and b as functions of Φ are

Parameter	Complex	Real	Description
T_o			Observation time per estimate.
V_{\max}			Maximum velocity seen by processing algorithm. ^a
ω			Spectral width of return signal.
SNR			Signal-to-noise ratio at processing bandwidth.
T_s	$\lambda/(4.V_{\max})$	$\lambda/(8.V_{\max})$	Time between samples.
M	T_o/T_s	T_o/T_s	Number of samples/estimate.
Ω	$\omega.M.T_s$	$\omega.M.T_s$	Effective number of independent samples/estimate.
Φ	SNR.M	SNR.M/2	Effective number of photo-electrons per estimate.

Table (3.3) Parameters used by the velocity estimator.

a. It should be noted that there has been some confusion over the definition of V_{\max} , for a processing window of $-V$ to $+V$ (ie maximum wind speed of V but with direction away from or towards the lidar), V_{\max} has been defined as $2.V$ or as V by various people. In this document V_{\max} is always defined as V .

given by the empirical relations:

$$\frac{g}{\omega}(\Phi) = \chi \left(1 + \left(\frac{\Phi}{g_0} \right)^\epsilon \right)^{-\delta} + \mu \quad (1.16)$$

and :

$$b(\Phi) = \left(1 + \left(\frac{\Phi}{b_0} \right)^\alpha \right)^{-\gamma} \quad (1.17)$$

Values of χ , g_0 , ϵ , δ , μ , b_0 , α and γ for various values of M and Ω are listed in Appendix C - Lidar Performance Calculation.

1.6 The lidar scan pattern

The model considers three different scan patterns, a simple conical scan where the whole telescope is pointed off nadir and rotated (the original LAWS scan technique), a conical scan using a rotating nadir pointing telescope with a front refracting element to scan the beam and a line scan mechanism similar to the French BEST scan pattern.

The shot pattern on the ground of the two conically scanned systems is the same, however the performance is different due to a reduction in the effective aperture of the telescope for the refracting element scanner. The effective telescope diameter, D_{eff} is:

$$D_{\text{eff}} = D \cos(\theta_n) \quad (1.18)$$

and it is this value that is used for the diameter in the SNR equation(1.6).

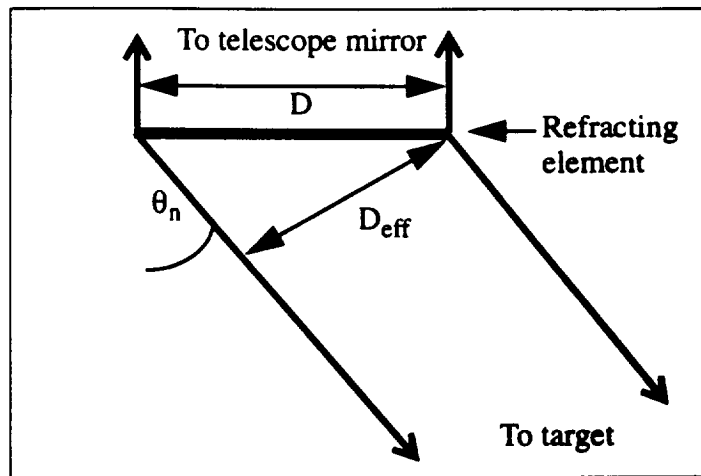


Figure (1.4) Geometry of effective beam diameter dependence on nadir angle.

The line scan technique is discussed in Appendix B- AEOLUS Telescope Geometry on page 32.

1.7 Results of the model

NASA Marshall Space Flight Center is in the process of conducting studies on a small satellite coherent Doppler wind lidar known as AEOLUS (Autonomous Earth Observing Lidar Utility Sensor). The model was used to assess the performance of four concepts under consideration for this instrument. Two of the concepts use a $9 \mu\text{m}$ CO_2 laser device whilst the remaining two concepts use a $2 \mu\text{m}$ Ho:Tm:YLF laser device. For each of the two wavelength options, two different shot scanning schemes were considered - a dual-telescope bi-perspective line scan scheme and a conical scan using a rotating refractive wedge element. The laser device characteristics were chosen as those most likely to be available for a space mission without incurring a heavy development cost penalty. The parameters used by the lidar model for each of these systems is given in Table (4.4).

Parameter	Design 1	Design 2	Design 3	Design 4	Units
Orbit					
Orbit height	350	350	350	350	km
Inclination angle	98	98	98	98	deg.
Laser					
Wavelength	9.11	9.11	2.06	2.06	μm
Pulse length	0.5	0.5	0.5	0.5	μs
Pulse energy	400	400	200	200	mJ
PRF	20	20	10	10	Hz
Orbit duty cycle	5	5	5	5	%
Optics					
Telescope diameter	0.5	0.5	0.5	0.5	m
Nadir angle	30	30	30	30	deg.
T_{tar}	0.9	0.9	0.9	0.9	
T_{rar}	0.9	0.9	0.9	0.9	
η_p	1	1	1	1	1
BPLO/signal beam alignment tolerance	13.91	16.07	3.15	3.64	μrad
Receiver					
Type	Complex	Complex	Complex	Complex	
Geometry	Wang	Wang	Wang	Wang	
Scan					
Type	Dual-look	Wedge	Dual-look	Wedge	
Telescope rotation rate	N.A.	12	N.A.	12	RPM
System margin	0.5	0.5	0.5	0.5	
Target					

Table (4.4) AEOLUS designs analysed.

Parameter	Design 1	Design 2	Design 3	Design 4	Units
Altitude	300	300	300	300	m
Max. horizontal velocity	30	30	30	30	m/s
Vertical range resolution	1000	1000	1000	1000	m

Table (4.4) AEOLUS designs analysed.

The BPLO/signal alignment angle tolerance was chosen to give a value of 0.5 for η_A . This enables the tolerance requirement for the two wavelengths to be compared. An additional parameter listed in the table is the system margin. Traditionally the predicted and measured performance of coherent Doppler lidars have differed. The system margin is a 3 dB allowance to ensure that the design of the instrument will be adequate for the task. The atmospheric model used for the atmospheric extinction coefficient, T_A was a mid-latitude summer clear aerosol model. This is the only atmosphere model that is included in the model at the moment and the data for this model were supplied by Coherent Technologies Inc., of Boulder, CO. Section shows some generic screen shots of the model (not for one of the four cases listed above). The performance of the lidar is generally characterised by two parameters, the backscatter value at which $b=0.5$ (1.17), i.e the velocity algorithm correctly determines the correct velocity 50 % of the time and by g (1.16) the standard deviation of the good velocity estimates about the true velocity. For the systems under consideration here the value of g at $b=0.5$ is always adequate for the task and so the performance of these systems can be characterised by the single parameter, $\beta(50\%)$ the value of aerosol backscatter at which $b=0.5$.

	Design 1	Design 2	Design 3	Design 4	
$\beta(50\%)$	7.8×10^{-9}	1.1×10^{-8}	5.1×10^{-8}	6.8×10^{-8}	/(m-sr)

Table (5.5)

It should be pointed out that the AEOLUS design is still being refined.

1.8 Summary

A model of a space-based coherent lidar has been developed and is being used to assess the performance of various instrument designs.

1.9 Screen shots of the model

The following pages show screen shots of various views of the model together with samples of the input parameter dialogs.

MSEC/USARadar Simulation (LIDAR.VXD)

File Edit Block Data Tools Graph Property Window Help

Instrument Parameters

ORBIT	
Orbit height	368 km
Inclination angle	98 deg

LASER	
Wavelength	9.1146187 µm
Pulse energy	8.4000 J
Pulse length	8.5 ps
Duty cycle	0.95
P.R.F.	28 Hz
Spectral width	8.3748 MHz
Frequency	32891748.83 MHz

RECEIVER	
Detector quantum efficiency	0.4
Transmit beam intensity fraction	0.955
Heterodyne efficiency	0.42
System efficiency	0.4011
Missalignment efficiency	0.500000328

SCANNING	
Scan type	Wedge
Plot duration	1 mins
Telescope rotation rate	12 rpm
(Conical/wedge scan only)	

SYSTEM	
System margin	0.5

OPTICS	
Telescope diameter	0.5 m
Field angle	38 deg
Transmit optics	0.9
Receive optics	0.9
Polarisation efficiency	1
Receiver misalignment angle	18.8873 rad
Effective diameter	8.433912782 m
(smaller for wedge scan)	
Rayleigh range	8.548136521 km
Beam spot size	8.137832224 m

Instrument

SIGNAL PROCESSING

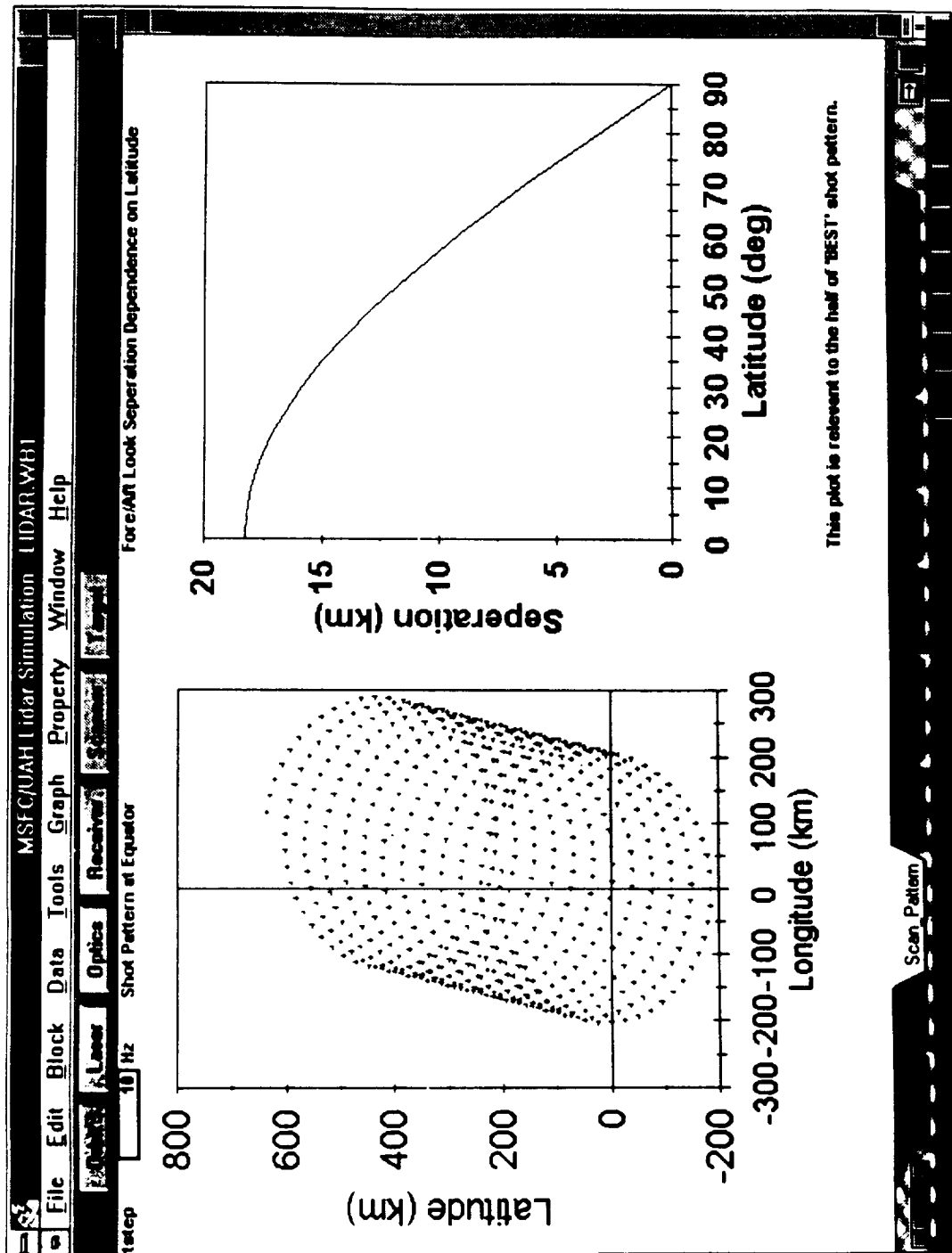
Aerosol altitude	300 m
backscatter (lambda)	1.35E-06 (m-ar)
Maximum horizontal velocity	30 m/s
Horizontal wind velocity uncertainty	0 m/s
Vertical wind velocity uncertainty	0 m/s
Wind variance between shots	0 m/s
Vertical range resolution	1000 m
Target nadir angle	31.81328 deg
Line of sight range to this altitude	407.5828 km
Coherence length	20.50846 m
One way Intensity Transmission	0.707307
Maximum line of sight velocity	15.82328 m/s

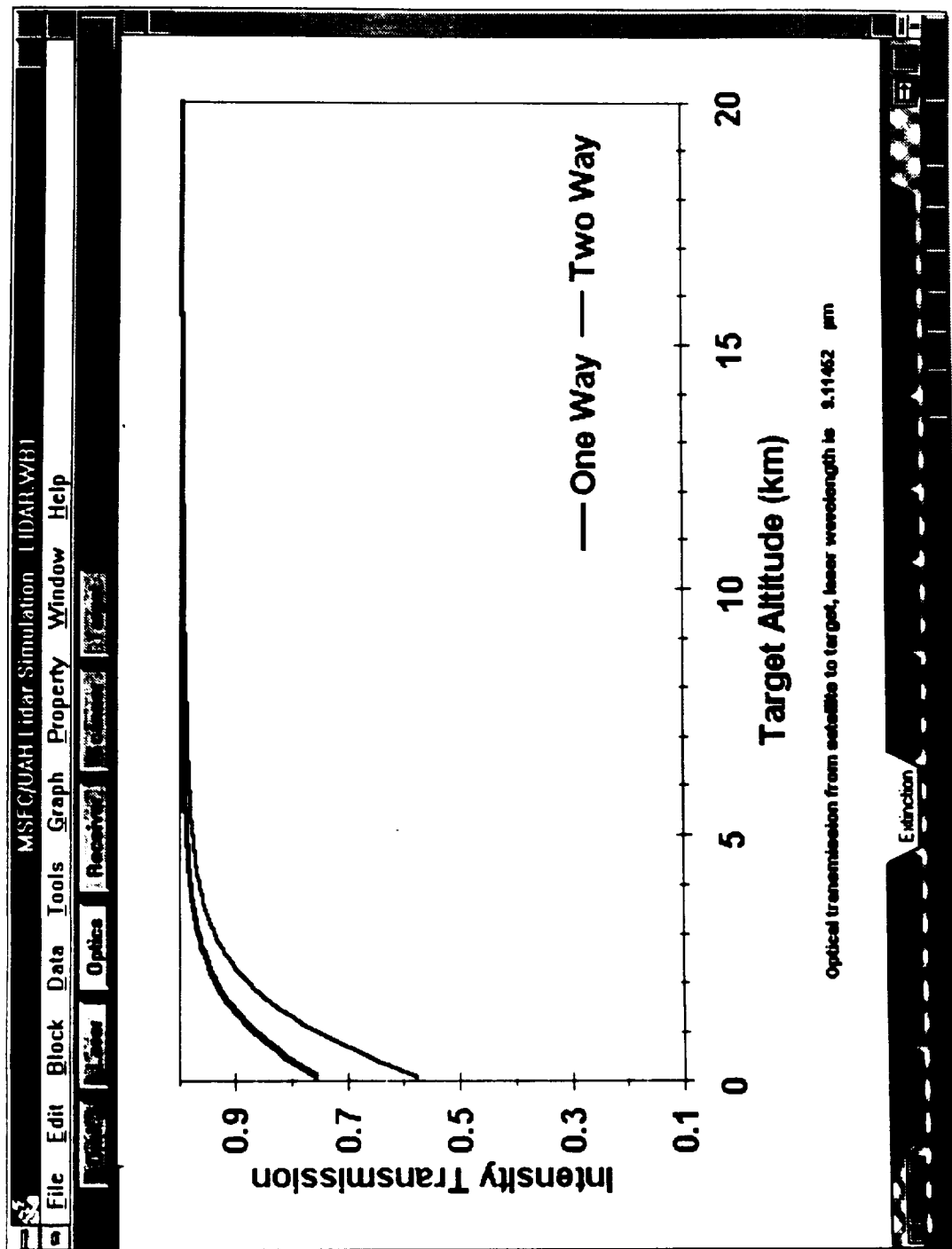
Line of sight range resolution	1177.9389	m
Observation time	7.8623	ps
Time between sample points	8.1948	ps
Digitalisation frequency	6.1646	MHz
No. sample points/observed	6.6283	
Phi	4.872	
Signal width	8.3748	MHz
Omega	2.8431	m/s
Signum/w	8.8297484	
No. of shots/ wind estimate	1	
Bandwidth (wide band)	6.9442	MHz
Bandwidth (narrow band)	8.3748	MHz
MIL E row no.	6	

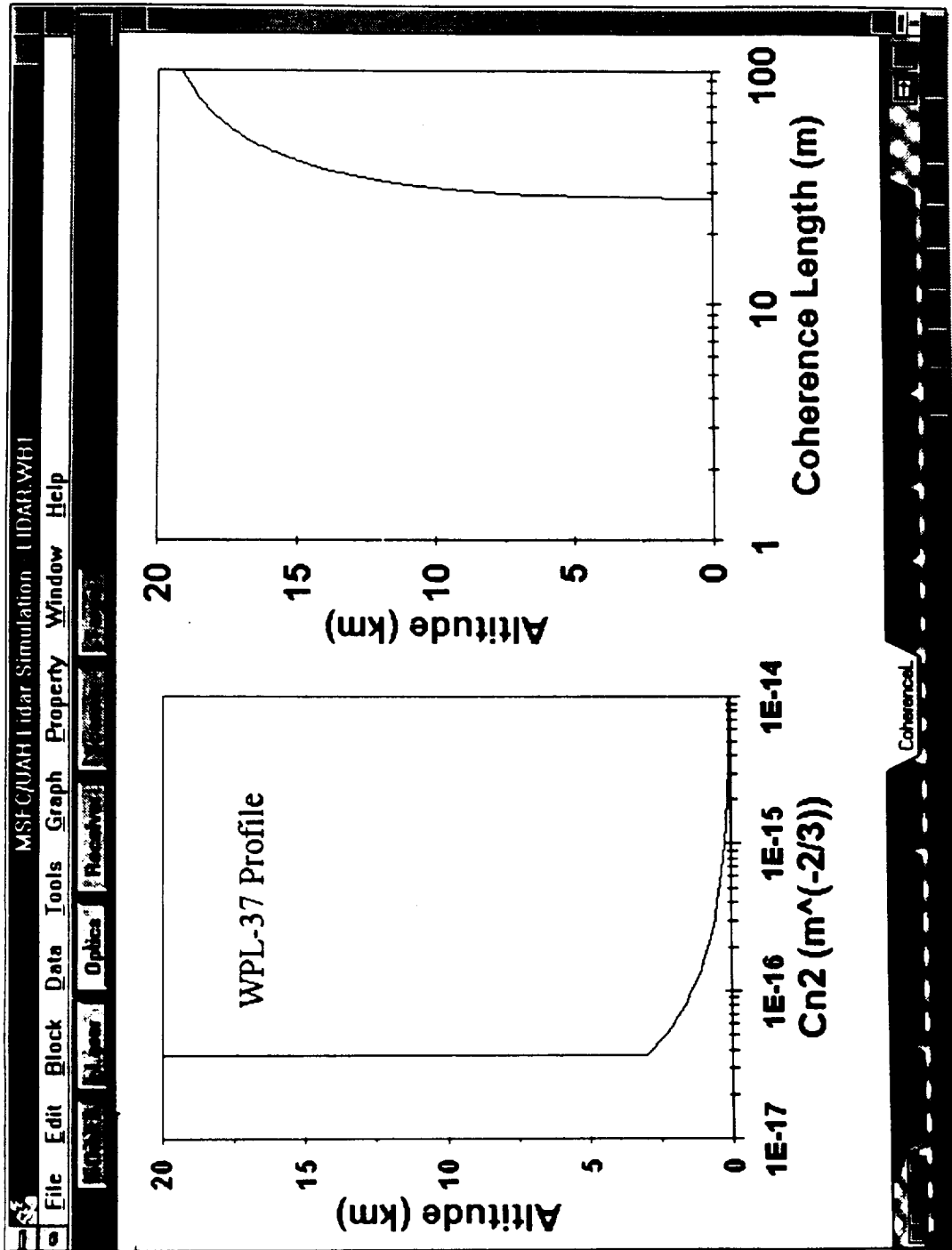
RESULTS

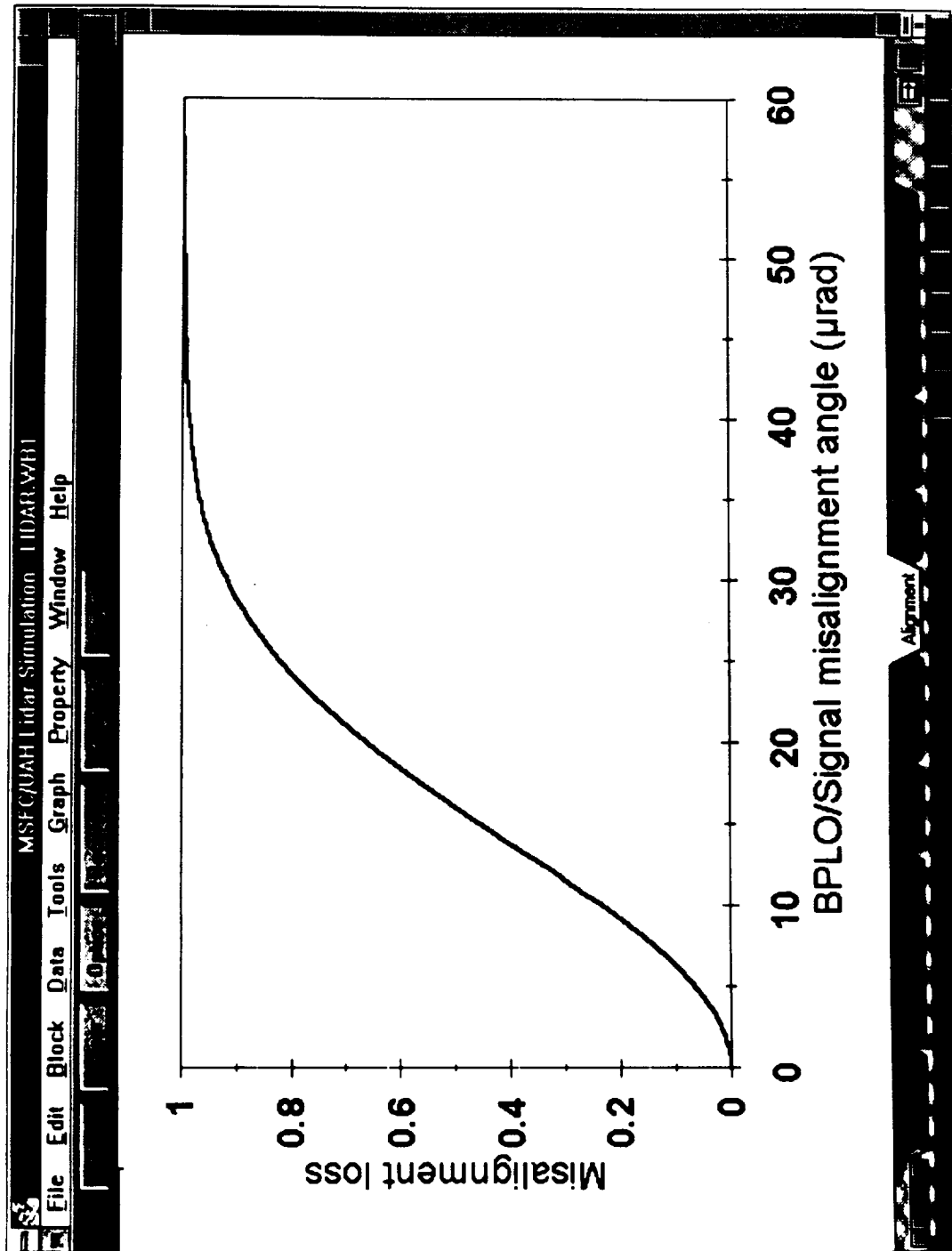
Satellite velocity	7784.321	m/s
ground track velocity	7363.133	m/s
Earth rotation velocity at equator	463.3367	m/s
Sleant range to ground	467817.5	m
Spot diameter on ground	18.9383	m
Time for one orbit	6481.694	s
Swath radius (conical/wedge scan)	20398.6	m
Optimum mirror flip time (line scan)	38.49824	s

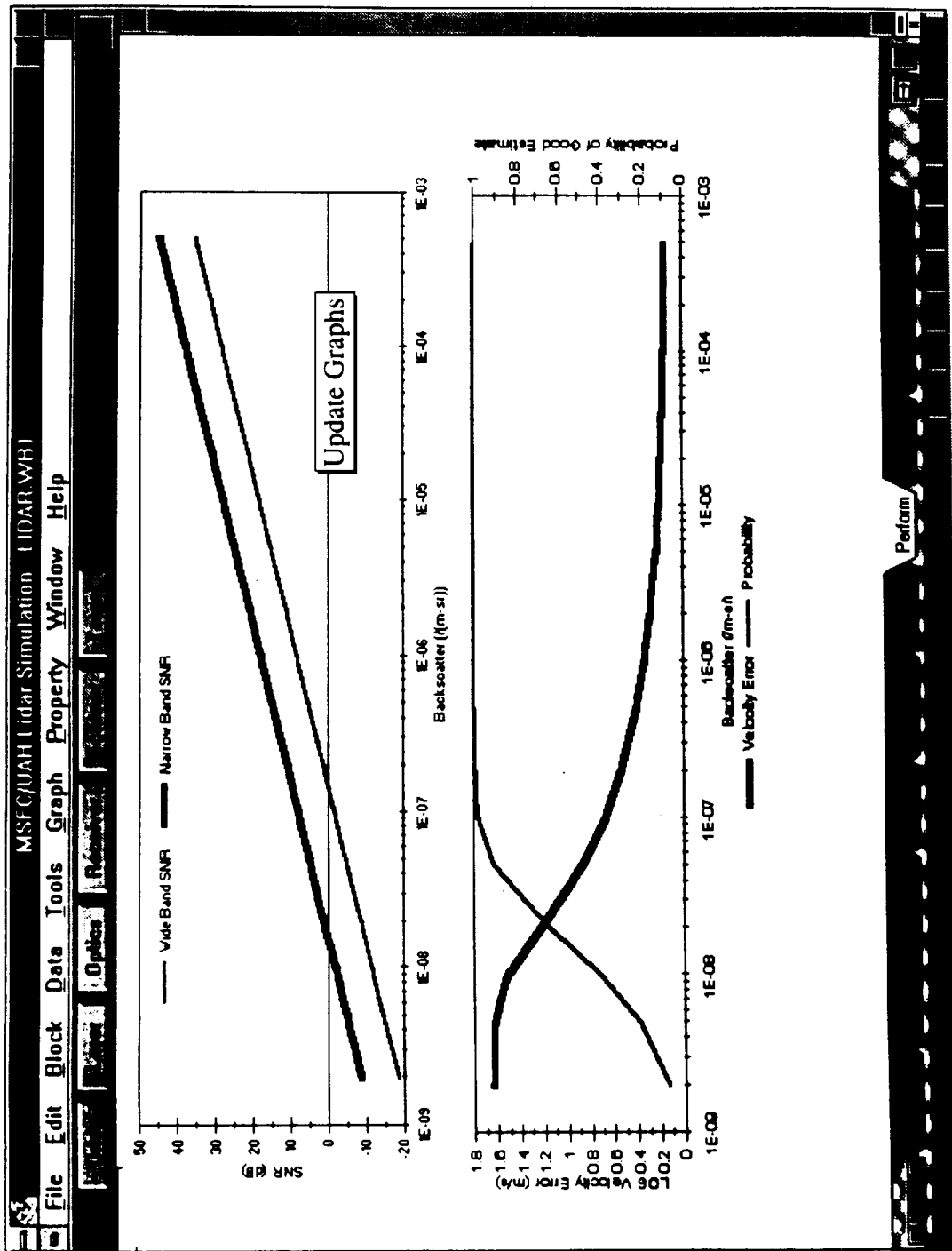
Wideband SNR	-10.400742	dB
Narrowband SNR	-6.7329153	dB
P(bad)	0.4005918	
P(good)	0.5914081	
sigmees - instrument	1.4018	m/s
sigmees	1.3730	m/s
F.O.M.	1.3682	
PH	4.9721866	



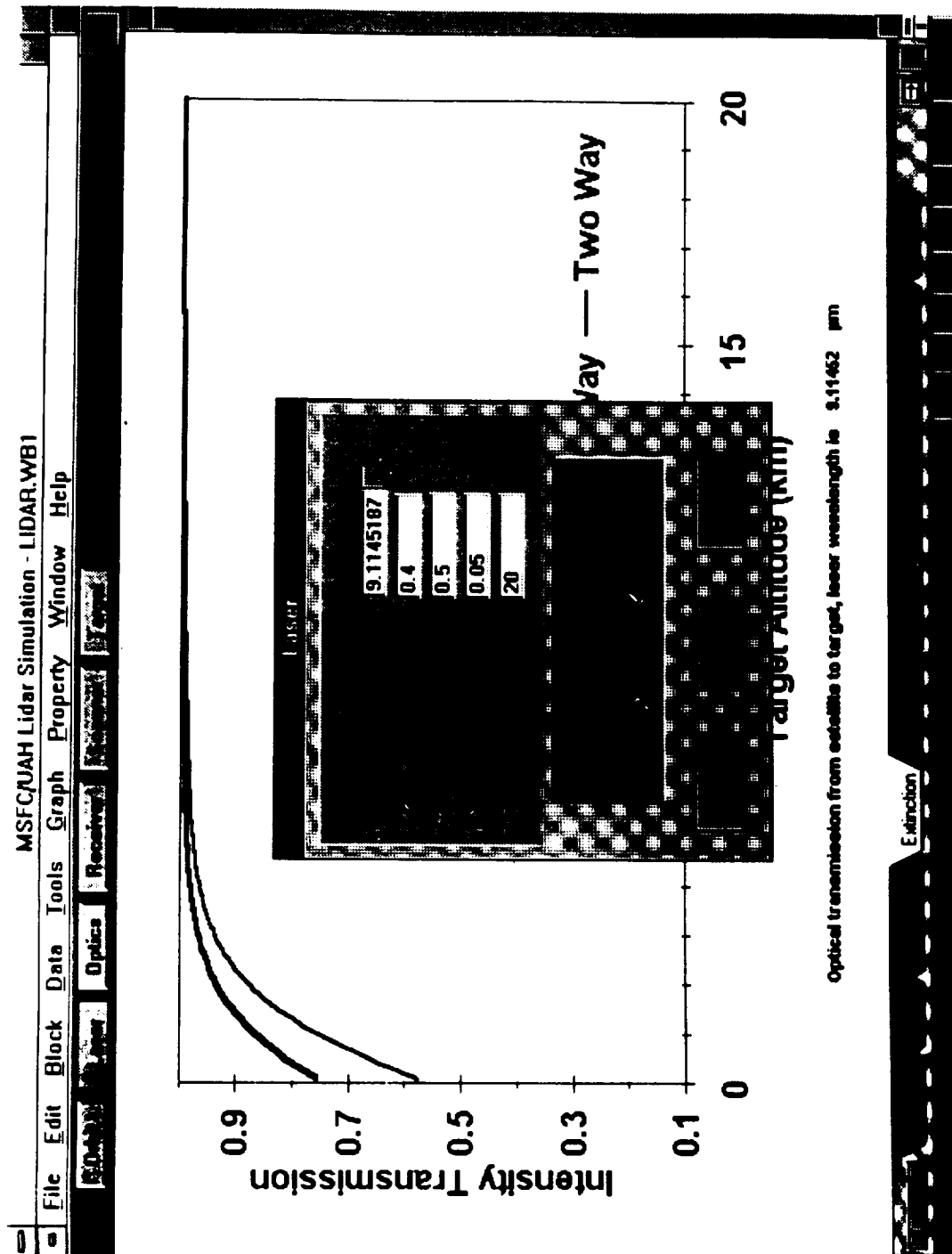








One benefit of having the input menus accessible from the button bar is the ability to change the lidar parameters from anywhere within the model. Changing the laser wavelength in this example would cause the extinction plot to automatically be recalculated and displayed for the user when the OK box on the input dialog is selected.



Samples of the other input dialog boxes.

Orbit

350

98

Receiver

Wang

0.4

Target

300

Target backscatter coefficient $1E-11$

Maximum horizontal velocity 30

Horizontal velocity 0

Vertical velocity 0

Shall be shot 0

1000

Optics

0.5

30

0.9

0.9

1

16.06673

0.5

Scanner

Wedge

1

12

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1.10 References

- [1] B.J. Rye, "Primary aberration contribution to incoherent backscatter heterodyne lidar returns.", Appl. Opt., 21, 839 - 844 (1982).
- [2] J.Y. Wang, "Optimum truncation of a lidar transmitted beam," Appl. Opt., 27, 4470 - 4474 (1988).
- [3] Barry J. Rye and Rod G. Frehlich, "Optimal truncation and optical efficiency of an apertured coherent lidar focused on an incoherent backscatter target.", Appl. Opt., 31, 15, 2891 - 2899 (1992).
- [4] David M. Tratt, "Optimizing coherent lidar performance with graded-reflectance laser resonator optics", Appl. Opt., 31, 21, 4233 - 4239 (1992).
- [5] R.M. Huffaker, ed., NOAA Technical Memorandum ERL WPL-37 (1978).
- [6] Michael J. Kavaya, Sammy W. Henderson, Edward C. Russell, R. Milton Huffaker and Rod G. Frehlich, "Monte Carlo computer simulations of ground-based and space-based coherent DIAL water vapor profiling.", Appl. Opt., 28, 5, 840 - 850 (1989).
- [7] C.W. Fairall and A.S. Frisch, "Diurnal and annual variations in mean profiles of C_n^2 .", NOAA Technical Memorandum ERL WPL-195, March 1991.
- [8] C.W. Fairall, Private Communication, May 1992.
- [9] Rod G. Frehlich, "Measurement of Heterodyne Efficiency for Diffuse or Aerosol Targets", To be published in J. Mod. Optics.
- [10] R.G. Frehlich and M.J. Yadlowsky, "Performance of mean-frequency estimations for Doppler radar and lidar", To be published in J. Atmos. Ocean. Tech.

2.0 Appendix A - Refractive Index Structure Function Calculation

2.1 Program structure

Program CN2CALG - main routine, allows user to select c_n^2 profile desired, determines routines to be used and calls them, saves results to output file called c_n^2 .dat. Output is in three columns, first column is altitude in km, second column is c_t^2 and third column is c_n^2 .

Subroutine CLRSCRN(I) - is a utility subroutine that scrolls the output screen by I lines. Called by the main program.

Function WPLCN(Z) - is a function for calculating the WPL-37 c_n^2 profile. For this c_n^2 case, the c_t^2 profile is not generated. Called by the main program.

Function CT2(Z,HP,P0,PBLZ,RNET,USTAR,ALPHA,BETA0) - is a function for calculating the c_t^2 value for a given altitude for all cases except the WPL-37 profile. This value is then used to calculate the value of c_n^2 (except for WPL-37). Called by the main program.

Function CN2(Z,HP,P0,CT,T0,ZT) - is a function for calculating the c_n^2 value at a given altitude for all cases except the WPL-37 profile. Called by the main program.

Function CTPBL(Z,PBLZ,ALPHA,RNET,BETA0,USTAR,T,DAY) - is a function for calculating the c_t^2 value in the planetary boundary layer. Called by function CT2.

2.2 Program code

2.2.1 Program CN2CALG

```
PROGRAM CN2CALG
C
  IMPLICIT NONE
C
  REAL*4 HP, P0, PBLZ, RNET, USTAR, ALPHA, OLDCT,
+ BETA0, T0, ZT, ETA, MAXZ, DZ, Z, CN2, CT, CN, CT2,
+ BETA(12), ALPH(12), U(12), NETR(12), ZPBL(12),
+ TZ(12), TEMPO(12), WPLCN
  INTEGER I, N, DAY, ILOCAL, ISEAS, ITIME, INDEX,
+ WPL
C
  PARAMETER (HP=6500., P0=1000.)
  MAXZ=20000.0
  N=500
  WPL=0
  OLDCT=0.0
C
  DATA BETA /2.,10.,1.,10.,0.25,10.,0.35,10.,0.25,0.25,0.25,0.25/
  DATA ALPH /0.2,0.9,0.4,0.9,0.2,0.9,0.2,0.9,0.93,0.93,0.93,0.93/
  DATA U /0.35,0.1,0.5,0.1,0.35,0.1,0.5,0.1,0.35,0.35,0.35,0.35/
  DATA NETR /600.,-100,300.,-100.,700.,-100.,350.,-100.,700.,
+ 700.,700.,700./
  DATA ZPBL /2000.,100.,1200.,100.,2000.,100.,2000.,100.,2000.,
+ 2000.,2000.,2000./
  DATA TZ /12000.,12000.,7000.,7000.,14000.,14000.,9000.,9000.,
```

```

+14000.,14000.,14000.,14000./
DATA TEMPO /298.,288.,278.,263.,303.,293.,288.,283.,303.,303.,
+303.,303./

```

C

```
CALL CLRSCRN(40)
```

C

```

WRITE(*,*)'This program calculates the refractive index'
WRITE(*,*)'structure constant, Cn2 for various locations,'
WRITE(*,*)'seasons and conditions. The calculation is'
WRITE(*,*)'based on NOAA Technical Memorandum ERL WPL-195'
WRITE(*,*)' "Diurnal and Annual Variations in Mean'
WRITE(*,*)'         Profiles of Cn2"'
WRITE(*,*)'         C.W. Fairall and A.S. Frisch'
WRITE(*,*)'         Wave Propagation Laboratory'
WRITE(*,*)'         Boulder, Colorado'
WRITE(*,*)'         March 1991'
WRITE(*,*)' '
WRITE(*,*)'         This program developed by:'
WRITE(*,*)'         Gary Spiers'
WRITE(*,*)'         Center for Applied Optics'
WRITE(*,*)'         University of Alabama in Huntsville'
WRITE(*,*)'         Huntsville, AL 35899.'
WRITE(*,*)

```

C

```
10 CALL CLRSCRN(2)
```

```

WRITE(*,*)'Please select one of these locations:-'
WRITE(*,*)
WRITE(*,*)' 1) Colorado'
WRITE(*,*)' 2) Florida'
WRITE(*,*)' 3) Trade Wind Oceans'
WRITE(*,*)' 4) WPL-37 Profile'
READ(*,*) ILOCAL

```

C

C

C

```
TRAP INVALID LOCATION
```

```

IF ((ILOCAL.LT.1).OR.(ILOCAL.GT.4)) THEN
  WRITE(*,*) 'Please choose a valid location!'
  GOTO 10

```

C

C

C

```
TRAP WPL EXPERIMENTAL PROFILE
```

```

ELSEIF (ILOCAL.EQ.4) THEN
  WPL=1

```

C

C

C

```
TRAP INCOMPLETE OCEAN TRADE WIND PROFILE
```

```

ELSEIF (ILOCAL.EQ.3) THEN
  WRITE(*,*)'At present this program only calculates a ',
+ 'daytime Trade Wind Profile.'
  ISEAS=1
  ITIME=1

```

C

C

C

```
DETERMINE SEASON AND TIME OF DAY FOR REMAINING CASES
```

```
ELSE
```

```

11 WRITE(*,*)
  WRITE(*,*)' Please select one of these seasons:-'
  WRITE(*,*)' 1) Summer'
  WRITE(*,*)' 2) Winter'
  READ(*,*) ISEAS
  IF ((ISEAS.LT.1).OR.(ISEAS.GT.2)) THEN
    WRITE(*,*)'Please choose a valid season option!'
    GOTO 11
  ENDIF
12 WRITE(*,*)

```

```

WRITE(*,*)'Please select the time of day:-'
WRITE(*,*)' 1) Daytime'
WRITE(*,*)' 2) Nighttime'
READ(*,*) ITIME
IF ((ITIME.LT.1).OR.(ITIME.GT.2)) THEN
  WRITE(*,*)' Please choose a valid time of day!'
  GOTO 12
ENDIF
ENDIF
C
WRITE(*,*)'Calculating...'
IF (WPL.EQ.0) THEN
  INDEX=(ILOCAL-1)*4+(ISEAS-1)*2+ITIME
  DAY=2-ITIME
  BETA0=BETA(INDEX)
  ALPHA=ALPH(INDEX)
  USTAR=U(INDEX)
  RNET=NETR(INDEX)
  PBLZ=ZPBL(INDEX)
  ZT=TZ(INDEX)
  T0=TEMPO(INDEX)
END IF
C
OPEN(UNIT=9,FILE='cn2.dat')
DZ=ALOG10(MAXZ)/N
DO 15 I=1,N
  Z=10.**(I*DZ)
  IF (WPL.EQ.1) THEN
    CT=0
    CN=WPLCN(Z)
  ELSE
    ETA= Z/PBLZ
    IF ((ETA .GE. 0.95) .AND. (ETA. LT. 1.0)) THEN
      CT=OLDCT
    ELSE
      CT=CT2(Z,HP,P0,PBLZ,RNET,USTAR,ALPHA,BETA0,
@    T0,DAY,ZT)
    ENDIF
    OLDCT=CT
    CN=CN2(Z,HP,P0,CT,T0,ZT)
  ENDIF
  WRITE(9,20) Z/1000,CT,CN
15 CONTINUE
20 FORMAT(3E15.8)
STOP
END

```

2.2.2 Subroutine CLRSCRN

```

SUBROUTINE CLRSCRN(I)
INTEGER J,I
DO 100 J=1,I,1
WRITE(*,*)
100 CONTINUE
RETURN
END

```

2.2.3 Function WPLCN

```
REAL*4 FUNCTION WPLCN(Z)
C
  IMPLICIT NONE
  REAL*4 Z
C
  IF (Z.LT.10.) THEN
    WPLCN=7.36*10.**(-14.)
  ELSEIF ((Z.GE.10.).AND.(Z.LT.3000.)) THEN
    WPLCN=1.59*10.**(-12.)*Z**(-4./3.)
  ELSEIF ((Z.GE.3000.).AND.(Z.LE.20000.)) THEN
    WPLCN=3.66*10.**(-17.)
  ELSE
    WPLCN=0.
  ENDIF
  RETURN
END
```

2.2.4 Function CT2

```
REAL*4 FUNCTION CT2(Z,HP,P0,PBLZ,RNET,USTAR,ALPHA,
  @BETA0,T0,DAY,ZT)
C
  IMPLICIT NONE
C
  REAL*4 HP,P0,DTROP,CTT,CTS,PBLZ,RNET,USTAR,ALPHA,
  *BETA0,T0,ZT,Z,P,T,CT,CTPBL
  INTEGER DAY
C
  PARAMETER (DTROP=2000.,CTT=8.E-5,CTS=1.E-3)
  P=P0*EXP(-Z/HP)
  IF (Z.LT.ZT) THEN
    T=T0-(T0-216.)*Z/ZT
  ELSE
    T=216.0
  ENDIF
  IF ((Z.LT.(ZT-DTROP)).AND.(Z.GE.PBLZ)) THEN
    CT2=CTT
  ELSEIF ((Z.GE.(ZT-DTROP)).AND.(Z.LE.(ZT+
  * DTROP))) THEN
    CT=(ALOG10(CTS)-ALOG10(CTT))*(Z-ZT)/(DTROP*2)
    * +(ALOG10(CTT)+ALOG10(CTS))/2
    CT2=10**(CT)
  ELSE
    CT2=CTS
  ENDIF
  IF (Z.LT.PBLZ) THEN
    CT2=CTPBL(Z,PBLZ,ALPHA,RNET,BETA0,USTAR,T,DAY)
  ENDIF
  RETURN
END
```

2.2.5 Function CN2

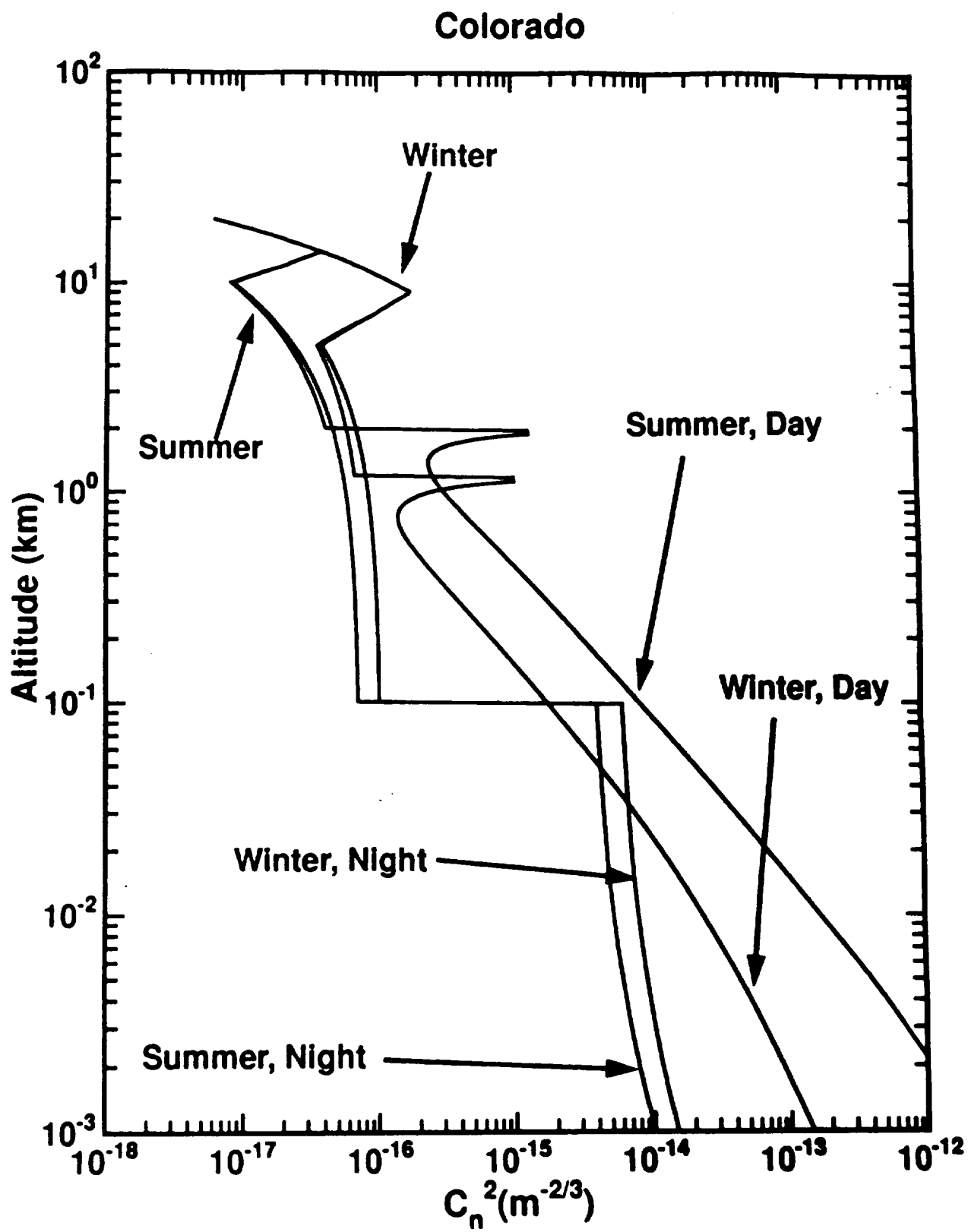
```
C      REAL*4 FUNCTION CN2(Z,HP,P0,CT,T0,ZT)
C
C      IMPLICIT NONE
C
C      REAL*4 HP,P0,Z,CT,T0,ZT,P,T
C
      P=P0*EXP(-Z/HP)
      IF (Z.LT.ZT) THEN
        T=T0-(T0-216.)*Z/ZT
      ELSE
        T=216.0
      ENDIF
      CN2=((7.9E-5*P/T**2)**2)*CT
      RETURN
      END
```

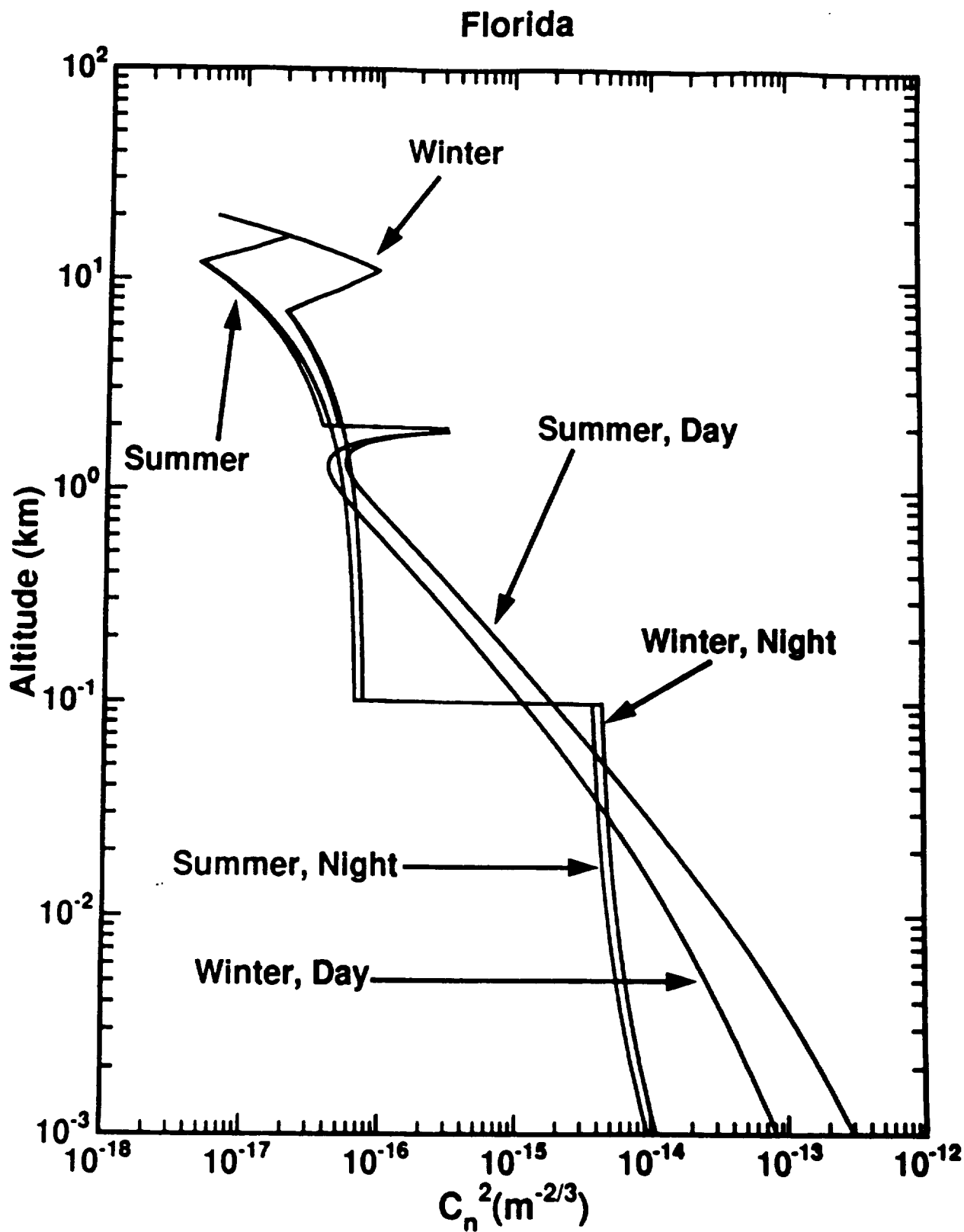
2.2.6 Function CTPBL

```
C      REAL*4 FUNCTION CTPBL(Z,PBLZ,ALPHA,RNET,BETA0,USTAR,T,DAY)
C
      IMPLICIT NONE
      REAL*4 Z,PBLZ,ETA,HSO,ALPHA,RNET,BETA0,TSTAR,RHOC,USTAR
*,L,KARMAN,G,WSTAR,T,THETA,HB,HTB,HT,RT
      INTEGER DAY

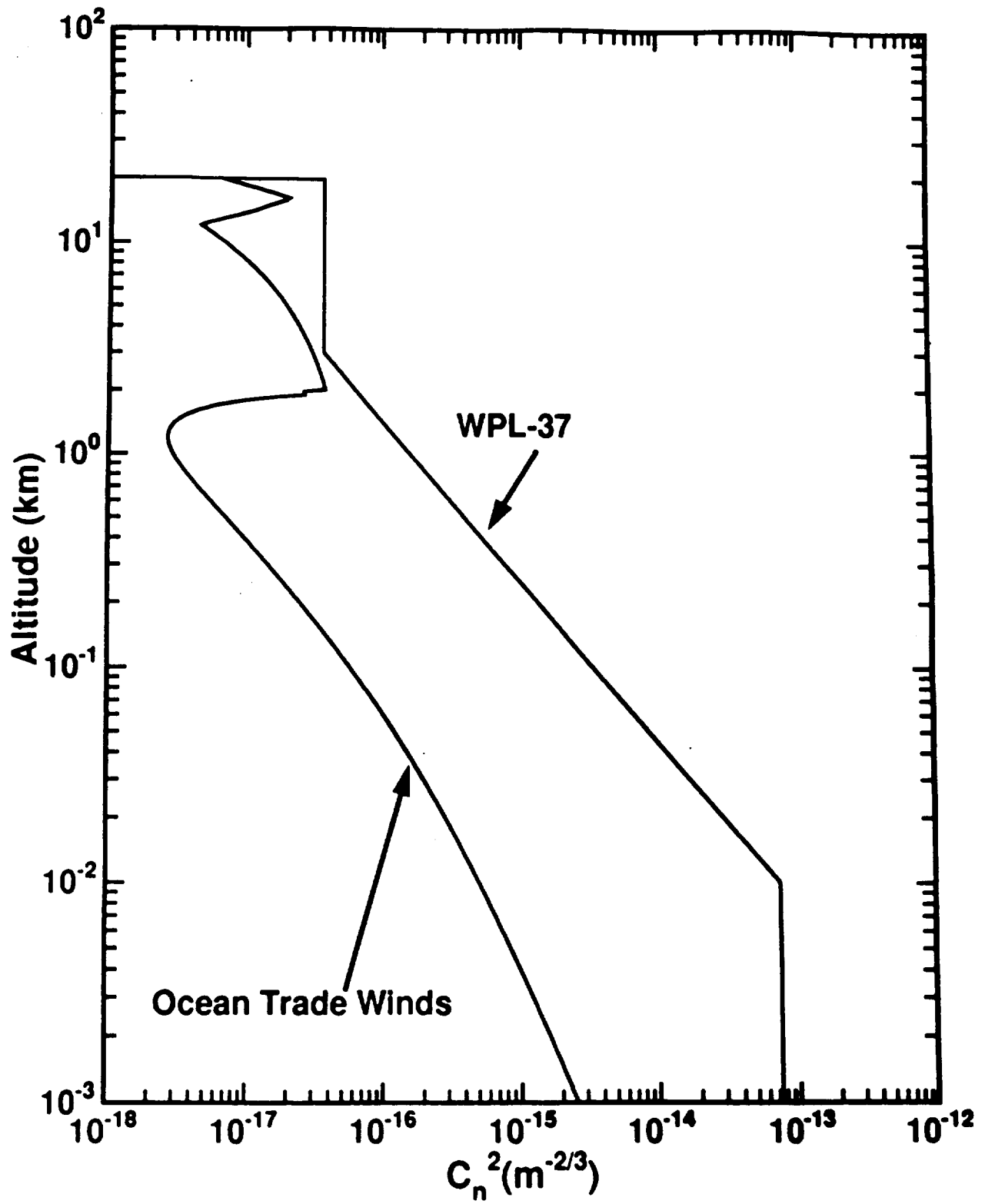
      PARAMETER (RHOC=1100, G=9.81, KARMAN=0.4)
      ETA=Z/PBLZ
      HSO=(1.-ALPHA)*RNET/(1.+1./BETA0)
      TSTAR=-HSO/(RHOC*USTAR)
      L=(T*USTAR**2)/(KARMAN*G*TSTAR)
      IF (DAY.EQ.1) THEN
        WSTAR=(-G/T)*USTAR*TSTAR/PBLZ)**(1./3.)
        THETA=-USTAR*TSTAR/WSTAR
        HB=10.*(-PBLZ/L)**(2./3.)*(ETA*(1.-7.*Z/L))**(-2./3.)
        HTB=8.*(1.-0.8*ETA)
        IF (ETA.GT.0.95) THEN
          HT=10.*(0.05)**(-3./2)/1.05
        ELSE
          HT=10.*(1.-ETA)**(-3./2)/(2.-ETA)
        ENDIF
        RT=-0.2*(1.+3.2*(-L/PBLZ))
        CTPBL=THETA**2*PBLZ**(-2./3.)*(HB+RT*HTB+RT**2*HT)
      ELSE
        CTPBL=TSTAR**2*Z**(-2./3.)*(1.+2.7*(Z/L)**(2./3.))
      ENDIF
      RETURN
      END
```

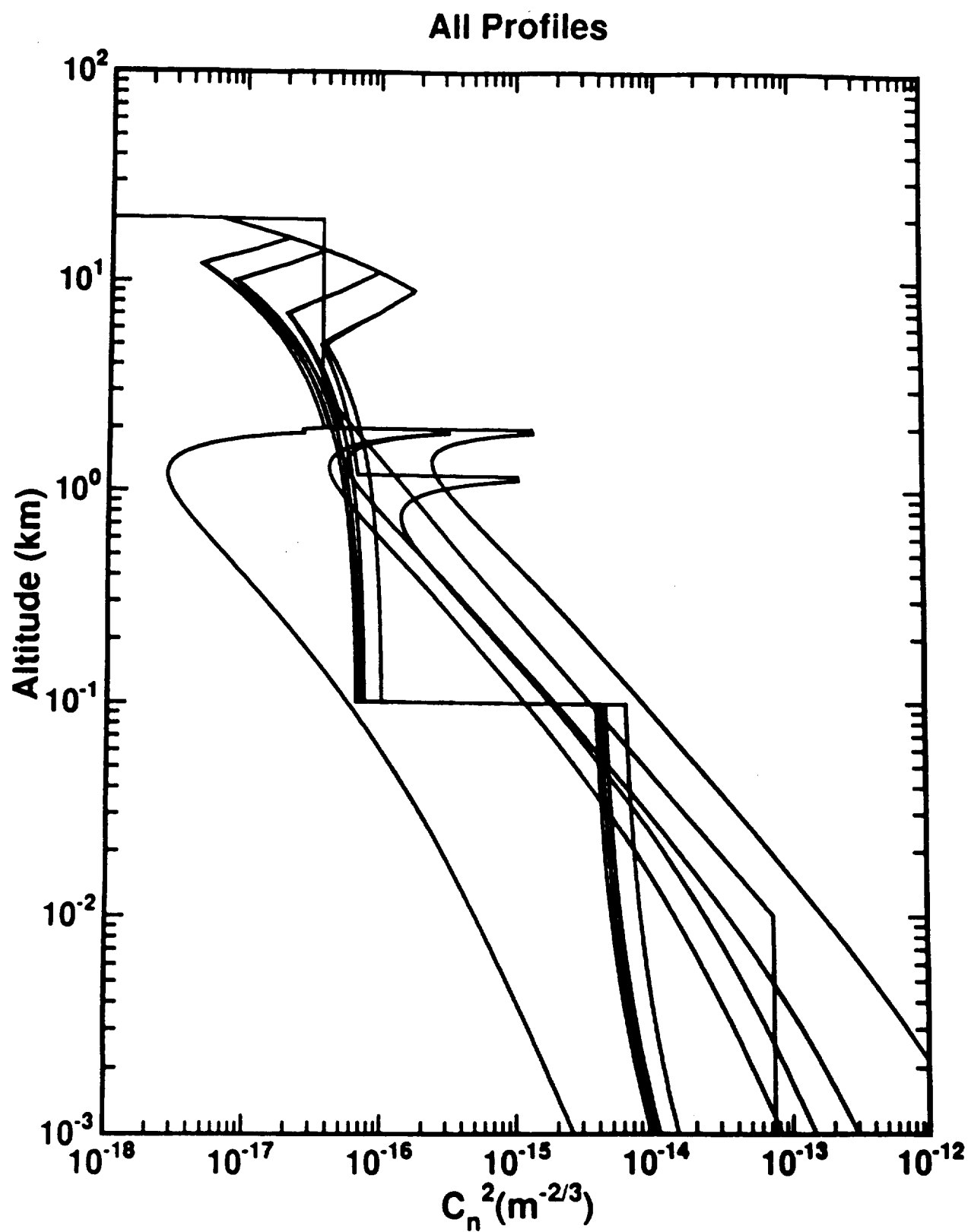
2.3 Plots of output results.





WPL-37 and Trade Winds





3.0 Appendix B- AEOLUS Telescope Geometry

This appendix was originally a memo released to the AEOLUS team on 9/29/93.

In this document, nadir always refers to the spacecraft nadir.

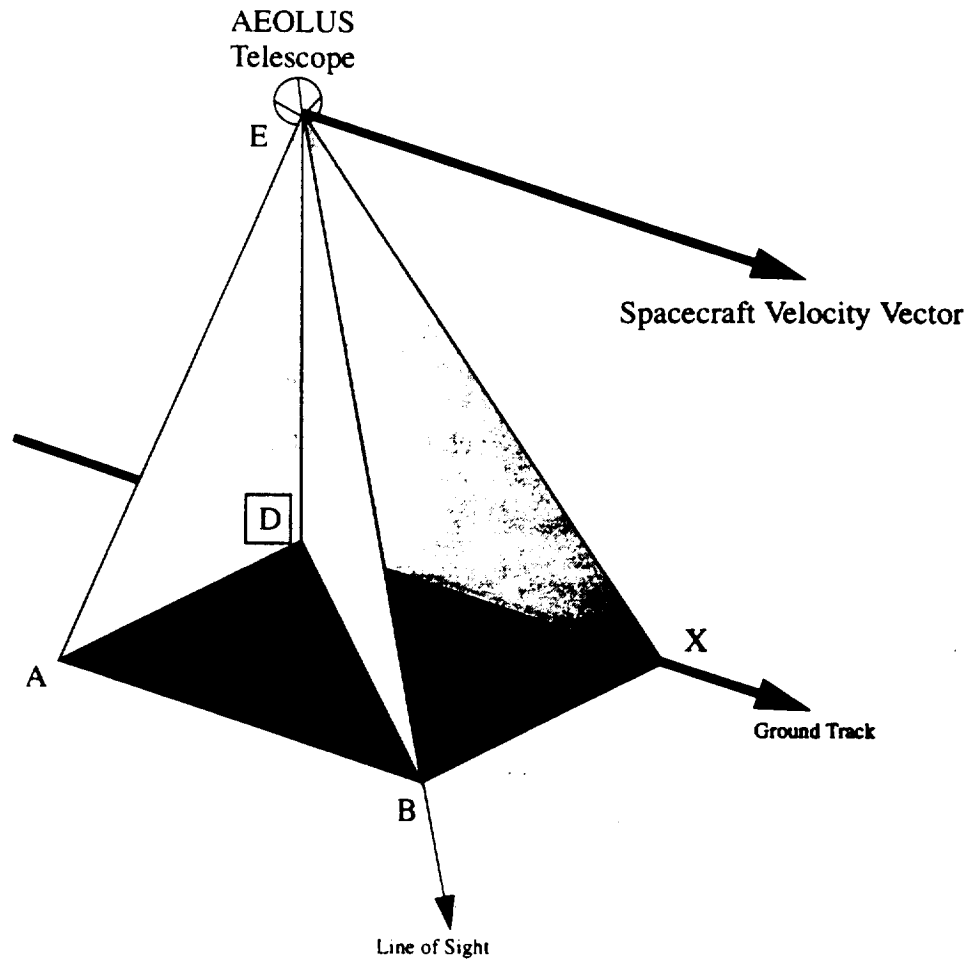


Figure (1.5) 3-D geometry.

3.1 Angle definitions

$\angle DEB = \theta_n$, the angle between the line of sight and nadir (nadir angle).

$\angle AED = \theta_R$, the angle between the left/right component of the line of sight and nadir.

$\angle DEC = \theta_F$, the angle between the forward/aft component of the line of sight and nadir.

Consider triangle DEB:

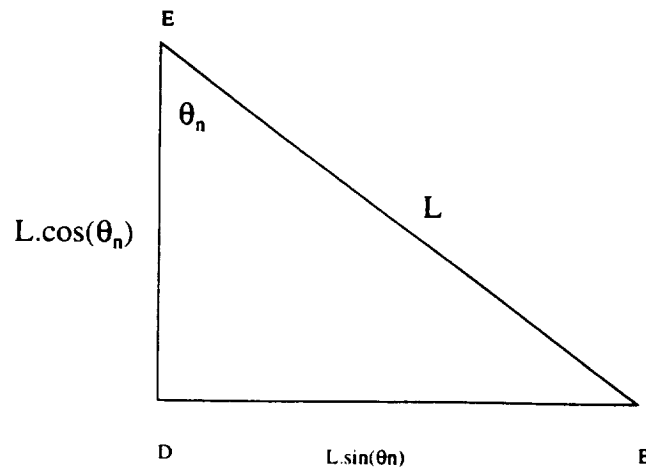


Figure (1.6) Triangle formed by line of sight and nadir.

Thus we have DE and DB in terms of L , the slant range to the ground and θ_n , the nadir angle. We can fold the triangles ADE and CDE into the ground plane ABCD:

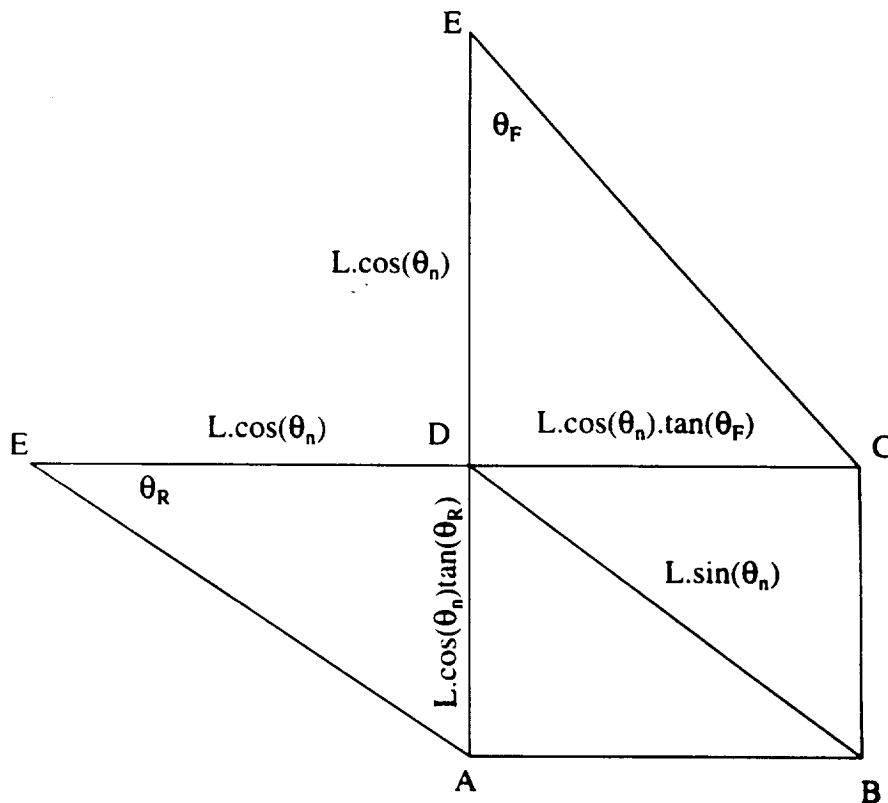


Figure (1.7) Folding of triangles ADE and CDE into the ground plane ABCD.

From Figure (1.6) we obtain expressions for ED and DB in Figure (1.7) and from Page (1) we have $\angle DEC = \theta_F$ and $\angle AED = \theta_R$. Simple trigonometry gives expressions for AD and CD. ABCD is a rectangle and so $AB = CD$. AD, AB and BD are related by Pythagoras' theorem:

$$AD^2 + AB^2 = BD^2 \quad (1.19)$$

substituting gives:

$$L^2 \cdot \cos^2(\theta_n) \cdot \tan^2(\theta_R) + L^2 \cdot \cos^2(\theta_n) \cdot \tan^2(\theta_F) = L^2 \cdot \sin^2(\theta_n) \quad (1.20)$$

dividing by $L^2 \cdot \cos^2(\theta_n)$ gives:

$$\tan^2(\theta_R) + \tan^2(\theta_F) = \tan^2(\theta_n) \quad (1.21)$$

Thus we have obtained an expression relating θ_n to θ_R and θ_F

3.2 Optimum geometry for wind velocity measurement.

Ideally we would like to resolve the wind velocity components along and perpendicular to the ground track with equal resolution. In Figure (1.7) these components are represented in the ground plane by DC and DA respectively and for them to have equal weighting we should therefore arrange the geometry such that:

$$DA = DC \quad (1.22)$$

Substituting values and simplifying gives:

$$\theta_R = \theta_F \quad (1.23)$$

Substituting back into Equation (1.21) gives:

$$2 \cdot \tan^2(\theta_F) = \tan^2(\theta_n) \quad (1.24)$$

rearranging to give θ_F as a function of θ_n :

$$\tan(\theta_F) = \tan(\theta_n) / \sqrt{2} \quad (1.25)$$

3.3 Angle between forward and aft view opticalaxes

For the dual telescope option, the angle, α between the forward and aft view optical axes is the angle between the forward and aft lines of sight. As the geometry is symmetric about the line perpendicular to the ground track, this angle is given by $2 \cdot \angle AEB$. Figure (1.8) shows the geometry for this calculation where B' is the aft-view point equivalent to B. We see that :

$$\sin(\alpha/2) = \cos(\theta_n) \cdot \tan(\theta_F) \quad (1.26)$$

substituting for $\tan(\theta_F)$ from Equation (1.25) and simplifying gives:

$$\alpha = 2 \cdot \sin^{-1}(\sin(\theta_n) / \sqrt{2}) \quad (1.27)$$

For AEOLUS we have $\theta_n = 30$ deg. and therefore $\alpha = 41.41$ deg. and $\theta_F = \theta_R = 22.21$ deg.

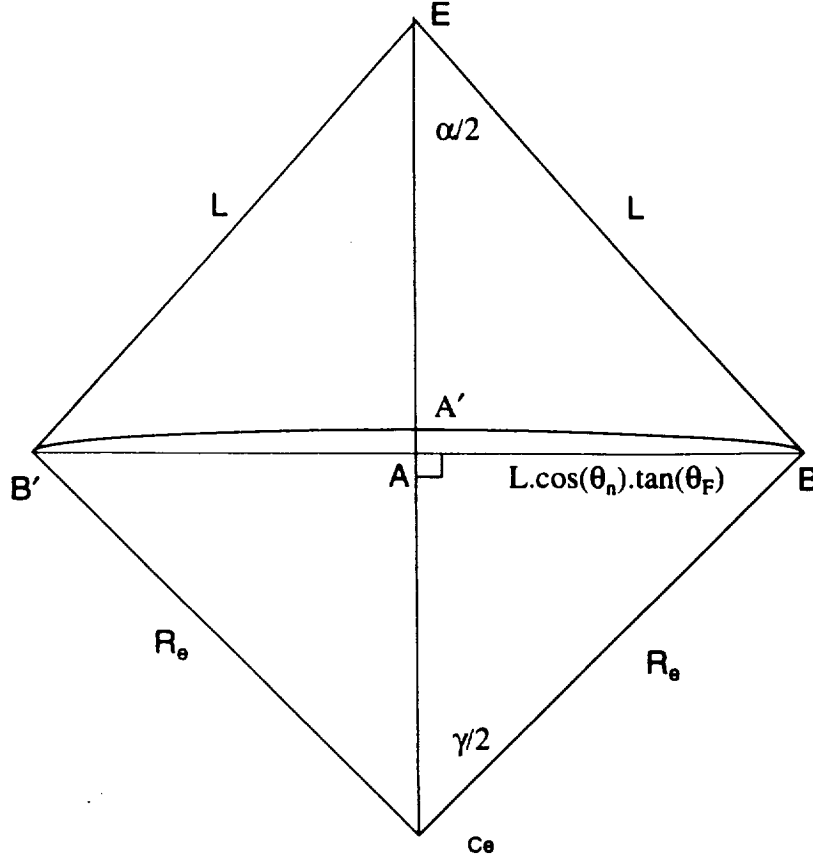


Figure (1.8) Geometry for telescope axis separation and path length on surface of earth.

3.4 Path length between forward and aft points on the ground.

Figure (1.8) also shows the center of the earth, C_e and the arc of the earth's surface $B'A'B$ between the forward and aft line of sight ground points. We see that $B'AB$ represents the chord linking these two points. From triangle ABC_e we can determine the half-angle subtended at the earth's center, $\gamma/2$ as:

$$\sin(\gamma/2) = L \cdot \cos(\theta_n) \cdot \tan(\theta_F) / R_e \quad (1.28)$$

The angle subtended by the earth's arc is γ and the length of the arc is given by $R_e \cdot \gamma$, where γ is in radians. This gives:

$$\text{track length} = 2 \cdot R_e \cdot \sin^{-1}(L \cdot \cos(\theta_n) \cdot \tan(\theta_F) / R_e) \quad (1.29)$$

For the AEOLUS conditions of $\theta_n = 0.5236$ (30 deg), $\theta_F = 0.3876$ (22.21 deg) and $R_e = 6371315$ m we have a line of sight length, L of 407916 m for a 350 km satellite altitude, assuming a spher-

ical earth. This gives a track length of 288498m between the forward and aft line of sight ground points. The ground track velocity is 7303 ms^{-1} and therefore the time to cover this distance will be 39.5 s. This means that to overlap the forward and aft views on the same patch of ground, the instrument should look in the forward direction for 39.5 s before changing to the aft view. At a constant PRF of 10 Hz the separation between pulses on the ground will therefore be 730.5 m, for a 20 Hz pulse rate this separation will reduce to 365.3 m.

3.5 Effect of varying θ_n .

The following plots show the variation of θ_R , θ_F and 2α as the nadir angle, θ_n varies between 0 deg. and 90 deg.

The first plot shows the dependence of θ_R on θ_F for various θ_n .

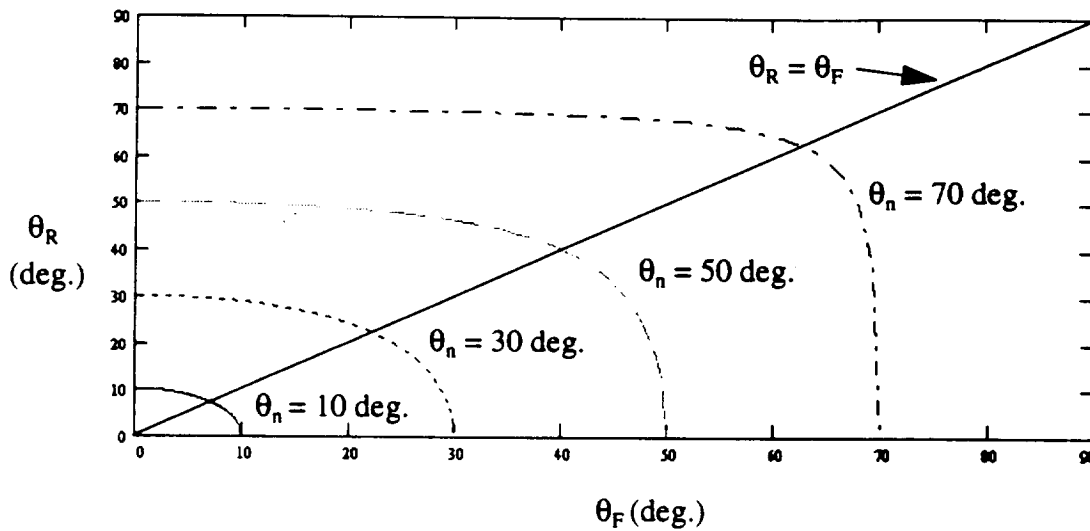


Figure (1.9) The dependence of θ_R on θ_F for various nadir angles, θ_n .

All of the remaining figures use the optimum geometry, $\theta_R = \theta_F$. It should be noted that for the orbit height under consideration, nadir angles greater than 70 deg. have not been considered as the line of sight does not contact the earth's surface at larger angles.

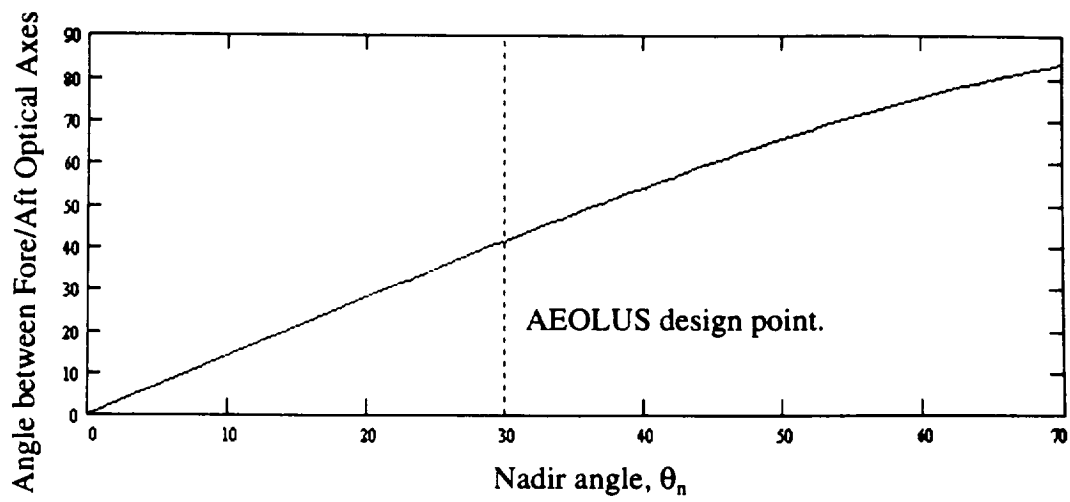


Figure (1.10) Dependence of fore/aft optical axes angular separation on nadir angle.

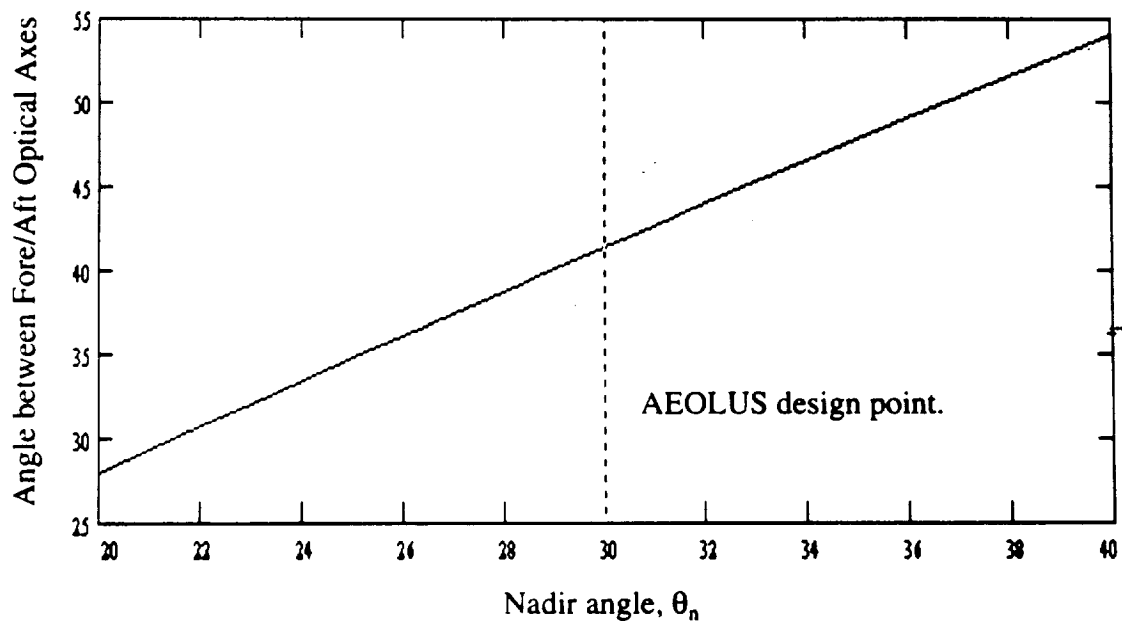


Figure (1.11) Expansion of Figure (1.10) to show region of interest.

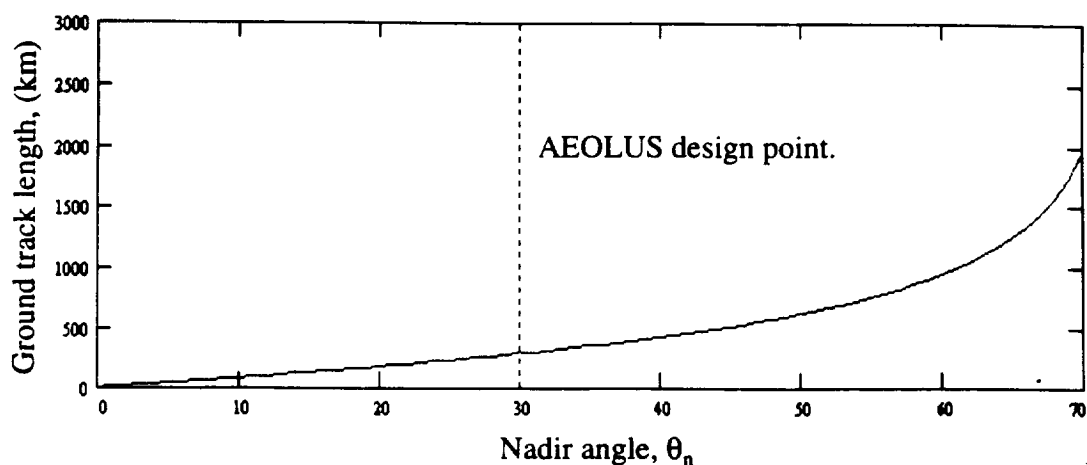


Figure (1.12) Dependence of the ground track length between the fore and aft line of sight ground points on nadir angle.

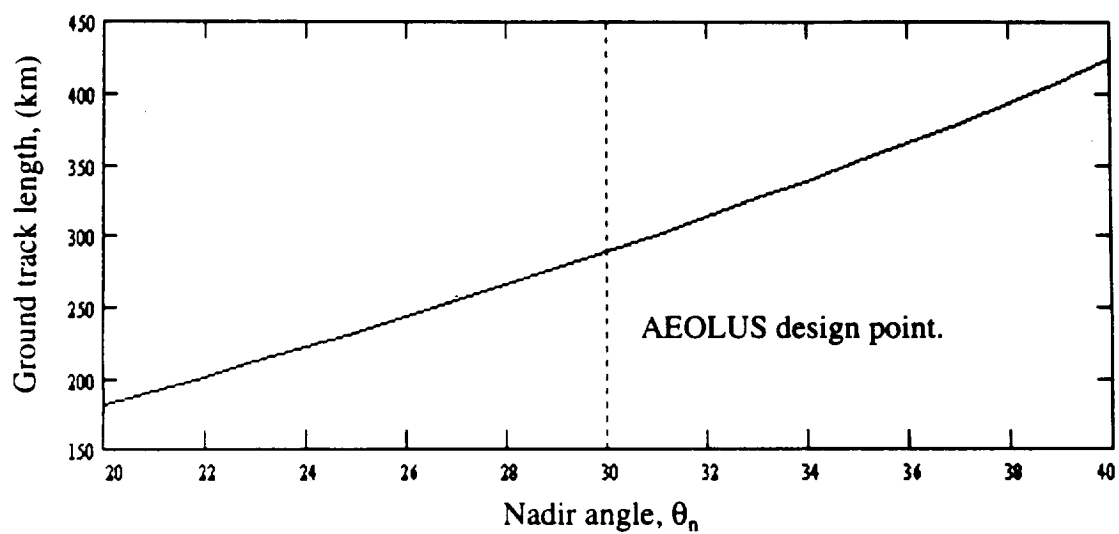


Figure (1.13) Expansion of Figure (1.12) to show the region of interest.

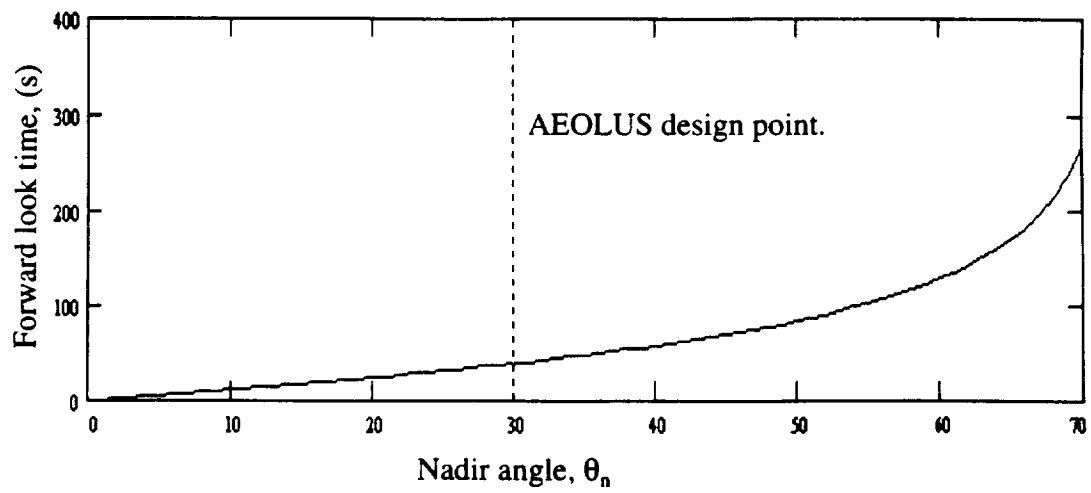


Figure (1.14) Dependence of forward look time on nadir angle.

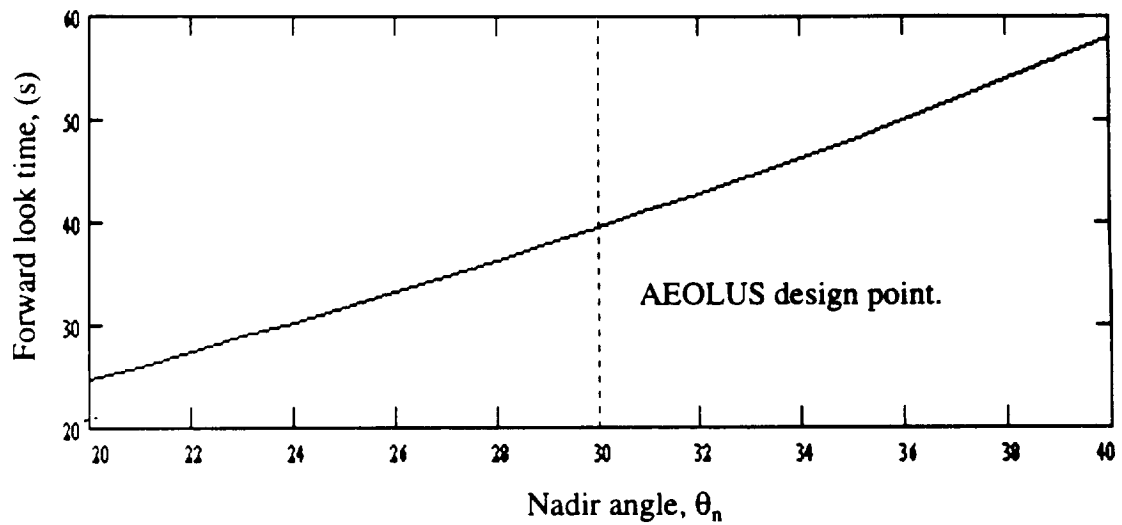


Figure (1.15) Expansion of Figure (1.14) to show the region of interest.

4.0 Appendix C - Lidar Performance Calculation

4.1 Description

This appendix lists the code used to generate the lidar model. Unlike conventional programming, spreadsheet programs do not consist of a linear list of commands but a series of expressions at various locations throughout the spreadsheet. The built-in code provided by the spreadsheet vendor enables a user interface to be created with relative ease. The nature of this program which centers on looking up values in assorted tables and then performing limited numerical calculations on them is ideally suited to a spreadsheet. Results can then easily be presented to the user through the use of the vendor supplied graph plotting routines.

This program consists of three files:-

- Lidar.WB1 - the main spreadsheet which obtains user inputs, performs calculations and presents results.
- Atmos.WB1 - a spreadsheet containing the atmospheric extinction as a function of altitude for a range of wavelengths.
- Lidar.BAR - a toolbar which is used to provide access to the input routines.

The program is written for the Borland Quattro-Pro for Windows spreadsheet. Each section of the code is contained on a separate notebook page of the spreadsheet. The code on each page is listed below. A 'user's view' of each page was provided in Section 1.9.

4.2 Using the program

To run the program, the user should place the three files listed above in a common directory. Quattro Pro for Windows should then be started and the file Lidar.WB1 loaded. When loading this program will ask if the user wishes to open supporting hotlinks (this refers to the Atmos.WB1 file). The answer to this question should be 'OK'. The Lidar.BAR speedbar is loaded as a second speedbar by following the instructions in the Quattro Pro documentation. It is intended to automate the start-up procedure at a later time. Once the program is loaded the user can select input parameters for the various lidar components by 'clicking' on the required component button on the speedbar and then changing the values in the dialog boxes. All plots update automatically (unless the user has explicitly turned off automatic update) except for the performance plot which is only updated when the 'Update Graphs' button on that page is selected.

At the time of this report additional velocity estimation parameter regimes were still being provided by Dr. Frehlich therefore a routine to automatically select the optimum parameterisation for a pair of Ω and M values had not been implemented. This means that the user must manually tell the spreadsheet which parameterisation to use. This is done by typing the row number of the closest Ω M pair on the velocity estimator look-up table into the cell labeled "MLE row no." on the Results page of the spreadsheet.

The code is still under development with current work concentrating on getting the code operational rather than 'bullet-proof' and so none of the help buttons currently provide messages and

the user is not protected from modifying the spreadsheet. A backup copy of the files should therefore be kept in another location.

4.3 Variable list

The following table lists the variables used and their locations. Spreadsheet cell references are of the form [SSNAME]PGNAME:CELL where SSNAME is the name of the relevant spreadsheet (defaults to active current spreadsheet if not supplied), PGNAME is the relevant page of the spreadsheet and CELL is the cell address on the page.

The values in this table were exported from the spreadsheet page Block_Names. Due to differences in the number of columns used in the spreadsheet and here the list is not in strict alphabetical order, where alphabetical order is not followed, a double horizontal line occurs in the table below.

Variable Name	Cell Location	Variable Name	Cell Location
ALIGNDAT	Alignment:A36..B173	EPSILON	ML_Estimator:I2
ALIGN_ANGLE	Instrument:C22	ETA_ALIGN	Alignment:B37
ALIGN_LOSS	Alignment:E44	ETA_EXTINCT	Extinction:C242
ALPHA	ML_Estimator:E2	ETA_HETERODYNE	Instrument:G8
ALT	Results:C2	ETA_HQE	Instrument:G6
ALTITUDE	Extinction:A37	ETA_MISALIGN	Instrument:G10
ALTITUDEI	CoherenceL:A37	ETA_POLARISE	Instrument:C21
ATTEN	Results:C13	ETA_SYSTEM	Instrument:G9
B	Results:G5	EXTINCTDAT	Extinction:A36..G237
B0	ML_Estimator:D2	FALSESPEC_MSG	messages:D3..H3
BETA	Results:C3	FREQ	Instrument:C14
BETA_CALC	Macros:B27	G	Constants:B7
BETA_COUNT	Macros:B9	G0	ML_Estimator:H2
BETA_RANGE	Perform:A36..A59	GAMMA	ML_Estimator:F2
C	Constants:B3	GEOMETRY	Instrument:G5
CHI	ML_Estimator:G2	GEOMETRY_TYPES	Lists:C2..G4
CN2	CoherenceL:E37	H	Constants:B2
COHERENCE	CoherenceL:C241	HCOHERENCE	Constants:B8

D	Instrument:C23	LAMBDA	Instrument:C8
DELTA	ML_Estimator:J2	LAMBDA_LIST	Lists:A1..A8
DUMMY1	Alignment:E43	LASER_DATA	Instrument:C8..C12
DUMMY2	Constants:B11	LATITUDE	Scan_Pattern:O38
DUTY	Instrument:C11	LOSRANGE	Results:G2
M	Results:G6	PHI	Results:G7
MARGIN	Instrument:G24	PLOTMINS	Instrument:G18
ME	Constants:B5	POLN	Instrument:C21
MIN_BETA_POINT	Macros:B10	PRF	Instrument:C12
MIN_PROB	Macros:B11	QE	Instrument:G6
MLS_CLEAR	Perform:B1..I202	R	Results:C10
MSG1	messages:B2..B7	RANGE	Extinction:D37
MSG2	messages:B9..B28	RANGE2	CoherenceL:C37
MSG3	messages:B30..B50	RE	Constants:B4
MTS	Results:G2	RECEIVER_DATA	Instrument:G4..G6
MU	ML_Estimator:K2	RECEIVER_GEOM	Lists:C1..G4
MULTIPLIER	CoherenceL:F37	RECEIVER_TYPE	Lists:I1..I2
NADALT	Results:C9	RHO0	Results:C11
NADALT1	Extinction:C37	RO	Instrument:C20
NADALT2	CoherenceL:B37	RPM	Instrument:G19
NADIR	Instrument:C18	RSWATH	Results:C26
NAROW_BANDWIDTH	Results:G13	SAVE_BETA	Macros:B8
NRG	Instrument:C9	SCANNER_DATA	Instrument:G17..G19
NSHOTS	Results:G11	SCAN_DATA	Instrument:G17..G19
ORBH	Instrument:C4	SCAN_FLAG	Scan_Pattern:J39
ORBINC	Instrument:C5	SCAN_TYPE	Instrument:G17
ORBIT_DATA	Instrument:C4..C5	SCAN_TYPE_LIST	Lists:J1..J3
PARAM	Alignment:A37	SIGMAM	Results:G24
PATH	Extinction:E37	SIGMAS	Results:C7

PATH2	CoherenceL:D37	SIGMAVLOS	Results:G25
PBAD	Results:G22	SIGMAV_H	Results:C5
PERFORMANCE	Perform:A36..E59	SIGMAV_I	Results:G24
PERFORM_CALC	Macros:B13	SIGMAV_V	Results:C6
PGOOD	Results:G23	SLANTG	Results:C23
SNR	Results:G20	TSTEP	Scan_Pattern:B1
SNR_NARROW	Results:G21	TT	Instrument:G7
SNR_WIDE	Results:G20	TTAR	Instrument:C19
SPOTG	Results:C24	T_SPEC_WIDTH	Constants:B9
SYSTEM	Instrument:G9	V1	Results:C21
TARGET_ALTITUDE	Results:C2	VEARTH	Results:C22
TARGET_DATA	Results:C2..C8	VERT_RANGE	Results:C8
TAU	Instrument:C10	VG	Results:C21
TE	Constants:B6	VMAXH	Results:C4
TEST	Extinction:L27	VMAXLOS	Results:C14
TFLIP	Results:C27	VSAT	Results:C20
TO	Instrument:C19	VSEARCH	Results:C4
TORBIT	Results:C25	W	Results:G8
TRAR	Instrument:C20	WIDE_BANDWIDTH	Results:G5
TS	Results:G4	WPL37DAT	CoherenceL:A36..F237
TSCOPE_D	Instrument:C17	\P	Perform:I40

4.4 Instrument

The following code lists the contents of cells on the instrument page. Text cells contain the initial characters, ', ^ and " which indicate left, center and right alignment respectively. Cell contents beginning with a + or @ are calculation cells. All of the cells are visible to the user.

```

Instrument:C1: 'Instrument Parameters
Instrument:B3: ^ORBIT
Instrument:F3: ^RECEIVER
Instrument:B4: "Orbit height
Instrument:C4: 350
Instrument:D4: 'km
Instrument:F4: "Type
Instrument:G4: 'Complex

```

```

Instrument:B5: "Inclination angle
Instrument:C5: 98
Instrument:D5: 'deg
Instrument:F5: "Geometry
Instrument:G5: 'Wang
Instrument:F6: "Detector quantum efficiency
Instrument:G6: 0.6
Instrument:B7: ^LASER
Instrument:F7: "Transmit beam intensity fraction
Instrument:G7: @VLOOKUP($GEOMETRY,$GEOMETRY_TYPES,1)
Instrument:B8: "Wavelength
Instrument:C8: 2.065479
Instrument:D8: 'µm
Instrument:F8: "Heterodyne efficiency
Instrument:G8: @VLOOKUP(GEOMETRY,GEOMETRY_TYPES,2)
Instrument:B9: "Pulse energy
Instrument:C9: 0.025
Instrument:D9: 'J
Instrument:F9: "System efficiency
Instrument:G9: +ETA_HETERODYNE*TT
Instrument:B10: "Pulse length
Instrument:C10: 0.5
Instrument:D10: 'us
Instrument:F10: "Misalignment efficiency
Instrument:G10: +ALIGN_LOSS
Instrument:B11: "Duty cycle
Instrument:C11: 0.05
Instrument:B12: "P.R.F.
Instrument:C12: 10
Instrument:D12: 'Hz
Instrument:B13: "Spectral width
Instrument:C13: +T_SPEC_WIDTH
Instrument:D13: 'MHz
Instrument:B14: "Frequency
Instrument:C14: +C/LAMBDA
Instrument:D14: 'MHz
Instrument:B16: ^OPTICS
Instrument:F16: ^SCANNING
Instrument:B17: "Telescope diameter
Instrument:C17: 0.25
Instrument:D17: 'm
Instrument:F17: "Scan type
Instrument:G17: 'Wedge
Instrument:B18: "Nadir angle
Instrument:C18: 30
Instrument:D18: 'deg
Instrument:F18: "Plot duration
Instrument:G18: 1
Instrument:H18: 'mins
Instrument:B19: "Transmit optics
Instrument:C19: 0.9
Instrument:F19: "Telescope rotation rate
Instrument:G19: 12
Instrument:H19: 'rpm
Instrument:B20: "Receive optics
Instrument:C20: 0.9
Instrument:F20: "(Conical/wedge scan only)
Instrument:B21: "Polarisation efficiency
Instrument:C21: 1
Instrument:B22: "Receive/lo misalignment angle
Instrument:C22: 7.2819023506228
Instrument:D22: 'µrad
Instrument:B23: "Effective diameter
Instrument:C23: @IF(SCAN_TYPE="Wedge",+TSCOPE_D*@COS(@RADIANS($NADIR)),TSCOPE_D)

```

```

Instrument:D23: 'm
Instrument:F23: ^SYSTEM
Instrument:B24: "(smaller for wedge scan)
Instrument:F24: "System margin
Instrument:G24: 0.5
Instrument:B25: "Rayleigh range
Instrument:C25: +D^2/(@PI*LAMBDA*10^-3)
Instrument:D25: 'km
Instrument:B26: "Beam spot size
Instrument:C26: +D/@PI
Instrument:D26: 'm

```

4.5 Results

The following code lists the cell contents of the results page. All of the cells are visible to the user.

```

Results:B1: ^TARGET
Results:F1: ^SIGNAL PROCESSING
Results:B2: "Aerosol altitude
Results:C2: 300
Results:D2: 'm
Results:F2: "Line of sight range resolution
Results:G2: +VERT_RANGE/@COS(@RADIANS(NADALT))
Results:H2: 'm
Results:B3: "backscatter (lambda)
Results:C3: 4.9E-06
Results:D3: '/(m-sr)
Results:F3: "Observation time
Results:G3: +LOSRANGE*2/(C*10^-6)
Results:H3: 'us
Results:B4: "Maximum horizontal velocity
Results:C4: 30
Results:D4: 'm/s
Results:F4: "Time between sample points
Results:G4: +LAMBDA/VMAXLOS*@IF(Instrument:$G$4="Complex",4,8)
Results:H4: 'us
Results:B5: "Horizontal wind velocity uncertainty
Results:C5: 0
Results:D5: 'm/s
Results:F5: "Digitisation frequency
Results:G5: 1/TS
Results:H5: 'MHz
Results:B6: "Vertical wind velocity uncertainty
Results:C6: 0
Results:D6: 'm/s
Results:F6: "No. sample points/observatn.
Results:G6: +G3/TS
Results:B7: "Wind variance between shots
Results:C7: 0
Results:D7: 'm/s
Results:F7: "Phi
Results:G7: 10^(SNR/10)*M/@IF(Instrument:$G$4="Complex",1,2)
Results:B8: "Vertical range resolution
Results:C8: 1000
Results:D8: 'm
Results:F8: "Signal width
Results:G8: @SQRT((0.1874/(TAU))^2+((SIGMAV_H/@SIN(@RADIANS(NADALT)))*2/
LAMBDA)^2+((SIGMAV_V/@COS(@RADIANS(NADALT)))*2/LAMBDA)^2)
Results:H8: 'MHz
Results:B9: "Target nadir angle
Results:C9: @DEGREES(@ASIN((ORBH*10^3+RE)*@SIN(@RADIANS(NADIR))/(RE+ALT)))
Results:D9: 'deg
Results:F9: "Omega

```



```

Results:G9: +W*G3
Results:H9: 'm/s
Results:B10: "Line of sight range to this altitude
Results:C10: @SQRT((($ORBH*10^3+$RE)^2+($RE+ALT)^2-(2*$ORBH*10^3+2*$RE)*
($RE+ALT)*@COS(@RADIANS(NADALT-$NADIR)))/1000
Results:D10: 'km
Results:F10: "Sigmax/w
Results:G10: @ARRAY((+@@("ML_Estimator:G"&@STRING(G14,0)))*(1+(PHI/
+@@("ML_Estimator:H"&@STRING(G14,0)))^+@@("ML_Estimator:I"&@STRING(G14,0)))^(-
@@("ML_Estimator:J"&@STRING(G14,0)))++@@("ML_Estimator:K"&@STRING(G14,0))))
Results:B11: "Coherence length
Results:C11: +COHERENCE
Results:D11: 'm
Results:F11: "No. of shots/ wind estimate
Results:G11: 1
Results:F12: "Bandwidth (wide band)
Results:G12: 4*VMAXLOS/LAMBDA
Results:H12: 'MHz
Results:B13: "One way Intensity Transmission
Results:C13: +ETA_EXTINCT
Results:F13: "Bandwidth (narrow band)
Results:G13: +W
Results:H13: 'MHz
Results:B14: "Maximum line of sight velocity
Results:C14: +VSEARCH*@SIN(@RADIANS(NADALT))
Results:D14: 'm/s
Results:F14: "MLE row no.
Results:G14: 6
Results:B19: ^OTHER PARAMETERS
Results:F19: ^RESULTS
Results:B20: "Satellite velocity
Results:C20: @SQRT(G*ME/(ORBH*10^3+RE))
Results:D20: 'm/s
Results:F20: "Wideband SNR
Results:G20: 10*@LOG((NRG*TT*TO*ATTEN^2*BETA*@PI*D^2*RO*SYSTEM*ETA_MISALIGN*
POLN*QE*C*$MARGIN)/(8*H*(FREQ*10^6)*SG$12*10^6*(R*1000)^2+(1+(D(2*RHO0))^2)))
Results:H20: 'dB
Results:B21: "ground track velocity
Results:C21: +VSAT*RE/(ORBH*10^3+RE)
Results:D21: 'm/s
Results:F21: "Narrowband SNR
Results:G21: 10*@LOG(10^(SNR/10)*2*VMAXLOS/(LAMBDA*W))
Results:H21: 'dB
Results:B22: "Earth rotation velocity at equator
Results:C22: 2*@PI*RE/TE
Results:D22: 'm/s
Results:F22: "P(bad)
Results:G22: @ARRAY((1+(PHI/+@@("ML_Estimator:D"&@STRING(G14,0)))^+@@("ML_Es-
timator:E"&@STRING(G14,0)))^-+@@("ML_Estimator:F"&@STRING(G14,0)))
Results:B23: "Slant range to ground
Results:C23: @SQRT((ORBH*10^3+RE)^2+RE^2-(2*ORBH*10^3+2*RE)*RE*@COS(@RADIAN-
S(NADALT-NADIR)))
Results:D23: 'm
Results:F23: "P(good)
Results:G23: 1-PBAD
Results:B24: "Spot diameter on ground
Results:C24: +$D*@SQRT(1+(LAMBDA*10^-6*SLANTG/(@PI*($D/2)^2))^2)
Results:D24: 'm
Results:F24: "sigmaxvlos - instrument
Results:G24: +G10*W*LAMBDA/2
Results:H24: 'm/s
Results:B25: "Time for one orbit
Results:C25: 2*@PI*(ORBH*10^3+RE)/VSAT
Results:D25: 's
Results:F25: "sigmaxvlos

```

```

Results:G25: @SQRT((SIGMAV_I^2+SIGMAS^2)/(NSHOTS*(1-PBAD)))
Results:H25: 'm/s
Results:B26: "Swath radius (conical/wedge scan)
Results:C26: 2*RE*@RADIANS(NADALT-NADIR)/2
Results:D26: 'm
Results:F26: "F.O.M.
Results:G26: ((ATTEN^2)/(R^2))*@SIN(@RADIANS(NADALT))*10^6
Results:B27: "Optimum mirror flip time (line scan)
Results:C27: 2*RE/V1*@ASIN(SLANTG*@SIN(@RADIANS(NADIR)))/(@SQRT(2)*RE))
Results:D27: 's
Results:F27: "PHI
Results:G27: +PHI

```

4.6 Scan pattern

The following code lists the contents of the Scan_Pattern page. The user sees two plots, one of the scan pattern and the other of the beam separation for the line scan pattern.

The following lines appear above the plots.

```

Scan_Pattern:A1: 'tstep
Scan_Pattern:B1: 1/(PLOTMINS*60/600)
Scan_Pattern:C1: 'Hz
Scan_Pattern:D1: 'Shot Pattern at Equator
Scan_Pattern:I1: 'Fore/Aft Look Separation Dependence on Latitude

```

The following line is visible to the user below the plots.

```

Scan_Pattern:I33: ' This plot is relevant to the half of 'BEST' shot pattern.

```

The remaining lines are out of sight from the user and are used to calculate the scan pattern. The model assumes that the satellite starts from 0 deg. latitude and 0 deg longitude. Columns B and C calculate the spacecraft latitude and longitude, column D calculates the telescope pointing angle with respect to the spacecraft velocity vector and, columns E and F calculate the position of the lidar beam on the ground (in km.) from the 0 deg. latitude, 0 deg. longitude position. Columns G and H calculate the beam separation for the line-scan pattern as a function of latitude. A total of 600 shot positions are calculated.

```

Scan_Pattern:B36: 'satellite track
Scan_Pattern:D36: 'angle
Scan_Pattern:B37: 'long
Scan_Pattern:C37: 'lat
Scan_Pattern:E37: 'long
Scan_Pattern:F37: 'lat
Scan_Pattern:G37: 'lat
Scan_Pattern:H37: 'separation
Scan_Pattern:A38: 0
Scan_Pattern:B38: +$A38/TSTEP*$V1*@COS(@RADIANS(180-$ORBINC))/1000+$A38/
$TSTEP*$VEARTH*@COS(@RADIANS($LATITUDE))/1000
Scan_Pattern:C38: +$A38/TSTEP*$V1*@SIN(@RADIANS(180-$ORBINC))/1000
Scan_Pattern:D38: @IF(@MOD($A38/$TSTEP,$TORBIT)>$TORBIT*$DUTY,0,@IF($SCAN_-
FLAG=1,$RPM/60*2*@PI*$A38/$TSTEP+0,@IF(@MOD(@INT($A38/$TSTEP/$TFLIP),2)>0,@RA-
DIANS(135),@RADIANS(45))))
Scan_Pattern:E38: +$B38+$RSWATH*@COS(@PI-@RADIANS($ORBINC)+$D38)/1000
Scan_Pattern:F38: +$C38+$RSWATH*@SIN(@PI-@RADIANS($ORBINC)+$D38)/1000
Scan_Pattern:G38: 0
Scan_Pattern:H38: +$VEARTH*$TFLIP*@COS(@RADIANS($G38))/1000

```

```

Scan_Pattern:N38: `latitude
Scan_Pattern:O38: 0
Scan_Pattern:P38: `deg
Scan_Pattern:A39: 1
Scan_Pattern:B39: +$A39/TSTEP*$V1*@COS(@RADIANS(180-$ORBINC))/1000+$A39/
$TSTEP*$VEARTH*@COS(@RADIANS($LATITUDE))/1000
Scan_Pattern:C39: +$A39/TSTEP*$V1*@SIN(@RADIANS(180-$ORBINC))/1000
Scan_Pattern:D39: @IF(@MOD($A39/$TSTEP,$TORBIT)>$TORBIT*$DUTY,0,@IF($SCAN_-
FLAG=1,$RPM/60*2*@PI*$A39/$TSTEP+0,@IF(@MOD(@INT($A39/$TSTEP/$TFLIP),2)>0,@RA-
DIANS(135),@RADIANS(45))))
Scan_Pattern:E39: +$B39+$RSWATH*@COS(@PI-@RADIANS($ORBINC)+$D39)/1000
Scan_Pattern:F39: +$C39+$RSWATH*@SIN(@PI-@RADIANS($ORBINC)+$D39)/1000
Scan_Pattern:G39: 5
Scan_Pattern:H39: +$VEARTH*$TFLIP*@COS(@RADIANS($G39))/1000
Scan_Pattern:J39: @IF(SCAN_TYPE="Dual-look",0,1)
Scan_Pattern:A40: 2
Scan_Pattern:B40: +$A40/TSTEP*$V1*@COS(@RADIANS(180-$ORBINC))/1000+$A40/
$TSTEP*$VEARTH*@COS(@RADIANS($LATITUDE))/1000
Scan_Pattern:C40: +$A40/TSTEP*$V1*@SIN(@RADIANS(180-$ORBINC))/1000
Scan_Pattern:D40: @IF(@MOD($A40/$TSTEP,$TORBIT)>$TORBIT*$DUTY,0,@IF($SCAN_-
FLAG=1,$RPM/60*2*@PI*$A40/$TSTEP+0,@IF(@MOD(@INT($A40/$TSTEP/$TFLIP),2)>0,@RA-
DIANS(135),@RADIANS(45))))
Scan_Pattern:E40: +$B40+$RSWATH*@COS(@PI-@RADIANS($ORBINC)+$D40)/1000
Scan_Pattern:F40: +$C40+$RSWATH*@SIN(@PI-@RADIANS($ORBINC)+$D40)/1000
Scan_Pattern:G40: 10
Scan_Pattern:H40: +$VEARTH*$TFLIP*@COS(@RADIANS($G40))/1000

```

The lines A40 - H40 are repeated, with column A being incremented by 1 each row and column G being incremented by 5 each row down to the following rows:-

```

Scan_Pattern:A55: 17
Scan_Pattern:B55: +$A55/TSTEP*$V1*@COS(@RADIANS(180-$ORBINC))/1000+$A55/
$TSTEP*$VEARTH*@COS(@RADIANS($LATITUDE))/1000
Scan_Pattern:C55: +$A55/TSTEP*$V1*@SIN(@RADIANS(180-$ORBINC))/1000
Scan_Pattern:D55: @IF(@MOD($A55/$TSTEP,$TORBIT)>$TORBIT*$DUTY,0,@IF($SCAN_F
LAG=1,$RPM/60*2*@PI*$A55/$TSTEP+0,@IF(@MOD(@INT($A55/$TSTEP/$TFLIP),2)>0,@RA-
DIANS(135),@RADIANS(45))))
Scan_Pattern:E55: +$B55+$RSWATH*@COS(@PI-@RADIANS($ORBINC)+$D55)/1000
Scan_Pattern:F55: +$C55+$RSWATH*@SIN(@PI-@RADIANS($ORBINC)+$D55)/1000
Scan_Pattern:G55: 85
Scan_Pattern:H55: +$VEARTH*$TFLIP*@COS(@RADIANS($G55))/1000
Scan_Pattern:A56: 18
Scan_Pattern:B56: +$A56/TSTEP*$V1*@COS(@RADIANS(180-$ORBINC))/1000+$A56/
$TSTEP*$VEARTH*@COS(@RADIANS($LATITUDE))/1000
Scan_Pattern:C56: +$A56/TSTEP*$V1*@SIN(@RADIANS(180-$ORBINC))/1000
Scan_Pattern:D56: @IF(@MOD($A56/$TSTEP,$TORBIT)>$TORBIT*$DUTY,0,@IF($SCAN_-
FLAG=1,$RPM/60*2*@PI*$A56/$TSTEP+0,@IF(@MOD(@INT($A56/$TSTEP/$TFLIP),2)>0,@RA-
DIANS(135),@RADIANS(45))))
Scan_Pattern:E56: +$B56+$RSWATH*@COS(@PI-@RADIANS($ORBINC)+$D56)/1000
Scan_Pattern:F56: +$C56+$RSWATH*@SIN(@PI-@RADIANS($ORBINC)+$D56)/1000
Scan_Pattern:G56: 90
Scan_Pattern:H56: +$VEARTH*$TFLIP*@COS(@RADIANS($G56))/1000

```

This completes the line-scan beam separation calculation and from this point only the shot pattern calculation is repeated until:-

```

Scan_Pattern:A637: 599
Scan_Pattern:B637: +$A637/TSTEP*$V1*@COS(@RADIANS(180-$ORBINC))/1000+$A637/
$TSTEP*$VEARTH*@COS(@RADIANS($LATITUDE))/1000
Scan_Pattern:C637: +$A637/TSTEP*$V1*@SIN(@RADIANS(180-$ORBINC))/1000

```

```

Scan_Pattern:D637: @IF(@MOD($A637/$TSTEP,$TORBIT)>$TORBIT*$DUTY,0,@IF($SCAN_
FLAG=1,$RPM/60*2*@PI*$A637/$TSTEP+0,@IF(@MOD(@INT($A637/$TSTEP/$TFLIP),2)>0,@-
RADIANS(135),@RADIANS(45)))
Scan_Pattern:E637: +$B637+$RSWATH*@COS(@PI-@RADIANS($ORBINC)+$D637)/1000
Scan_Pattern:F637: +$C637+$RSWATH*@SIN(@PI-@RADIANS($ORBINC)+$D637)/1000
Scan_Pattern:A638: 600
Scan_Pattern:B638: +$A638/$TSTEP*$V1*@COS(@RADIANS(180-$ORBINC))/1000+$A638/
$TSTEP*$VEARTH*@COS(@RADIANS($LATITUDE))/1000
Scan_Pattern:C638: +$A638/$TSTEP*$V1*@SIN(@RADIANS(180-$ORBINC))/1000
Scan_Pattern:D638: @IF(@MOD($A638/$TSTEP,$TORBIT)>$TORBIT*$DUTY,0,@IF($SCAN_
FLAG=1,$RPM/60*2*@PI*$A638/$TSTEP+0,@IF(@MOD(@INT($A638/$TSTEP/$TFLIP),2)>0,@-
RADIANS(135),@RADIANS(45)))
Scan_Pattern:E638: +$B638+$RSWATH*@COS(@PI-@RADIANS($ORBINC)+$D638)/1000
Scan_Pattern:F638: +$C638+$RSWATH*@SIN(@PI-@RADIANS($ORBINC)+$D638)/1000

```

4.7 Extinction

The following is a list of the code on the Extinction page. The user sees a plot of the one-way and two-way transmission of the atmosphere over the altitude range 0 - 20 km. The following lines are visible to the user beneath the plot.

```

Extinction:D33: 'Optical transmission from satellite to target, laser wave-
length is
Extinction:K33: +LAMBDA
Extinction:L33: 'um

```

The following lines are not visible to the user and are used to calculate the the one-way and two-way atmospheric extinction. Column A contains the altitude above the earths surface (incremented in 0.1 km steps), column C contained the nadir angle at that altitude (accounting for the earths curvature), column D contains the range from the satellite to the altitude and column E the path length from one altitude increment to the next. Column F contains the atmospheric extinction at the current altitude, column G the product of the path length and extinction, column H the summation of the path length/extinction products from the spacecraft to the current altitude. Column I contains the one-way extinction to the altitude and column J the two-way extinction.

```

Extinction:A36: 'Altitude
Extinction:B36: 'Index
Extinction:C36: 'Nadalt1
Extinction:D36: 'range
Extinction:E36: 'path
Extinction:F36: +LAMBDA
Extinction:G36: "lamda*path1
Extinction:I36: 'One Way
Extinction:J36: 'Two Way
Extinction:A37: 0
Extinction:B37: 1
Extinction:C37: @DEGREES(@ASIN((ORBH*10^3+RE)*@SIN(@RADIANS(NADIR)))/(RE+ALTI-
TUDE*1000)))
Extinction:D37: @SQRT((($ORBH*10^3+$RE)^2+($RE+ALTITUDE*1000)^2-
(2*$ORBH*10^3+2*$RE)*($RE+ALTITUDE*1000)*@COS(@RADIANS(NADALT1-$NADIR)))/1000
Extinction:E37: 0
Extinction:F37: @HLOOKUP($LAMBDA,(\QPW\LIDAR\ATMOS)$MLS_CLEAR,$B37)
Extinction:G37: 0
Extinction:H37: @SUM($G37..$G$237)
Extinction:I37: @EXP(-H37)
Extinction:J37: +I37^2
Extinction:A38: 0.1
Extinction:B38: 2

```

```

Extinction:C38: @DEGREES(@ASIN((ORBH*10^3+RE)*@SIN(@RADIANS(NADIR)) /
(RE+$A38*1000)))
Extinction:D38: @SQRT((($ORBH*10^3+$RE)^2+($RE+$A38*1000)^2-(2*$ORBH*10^3+2*
$RE)*($RE+$A38*1000)*@COS(@RADIANS($C38-$NADIR)))/1000
Extinction:E38: +RANGE-$D38
Extinction:F38: @HLOOKUP($LAMBDA, [\QPW\LIDAR\ATMOS]$MLS_CLEAR, $B38)
Extinction:G38: +$E38*$F38
Extinction:H38: @SUM($G38..$G$237)
Extinction:I38: @EXP(-H38)
Extinction:J38: +I38^2

```

A38 - J38 are repeated (with suitable incrementing) until:-

```

Extinction:A236: 19.9
Extinction:B236: 200
Extinction:C236: @DEGREES(@ASIN((ORBH*10^3+RE)*@SIN(@RADIANS(NADIR)) /
(RE+$A236*1000)))
Extinction:D236: @SQRT((($ORBH*10^3+$RE)^2+($RE+$A236*1000)^2-(2*$ORBH*10^3+
2*$RE)*($RE+$A236*1000)*@COS(@RADIANS($C236-$NADIR)))/1000
Extinction:E236: +$D235-$D236
Extinction:F236: @HLOOKUP($LAMBDA, [\QPW\LIDAR\ATMOS]$MLS_CLEAR, $B236)
Extinction:G236: +$E236*$F236
Extinction:H236: @SUM($G236..$G$237)
Extinction:I236: @EXP(-H236)
Extinction:J236: +I236^2
Extinction:A237: 20
Extinction:B237: 201
Extinction:C237: @DEGREES(@ASIN((ORBH*10^3+RE)*@SIN(@RADIANS(NADIR)) /
(RE+$A237*1000)))
Extinction:D237: @SQRT((($ORBH*10^3+$RE)^2+($RE+$A237*1000)^2-(2*$ORBH*10^3+
2*$RE)*($RE+$A237*1000)*@COS(@RADIANS($C237-$NADIR)))/1000
Extinction:E237: +$D236-$D237
Extinction:F237: @HLOOKUP($LAMBDA, [\QPW\LIDAR\ATMOS]$MLS_CLEAR, $B237)
Extinction:G237: +$E237*$F237
Extinction:H237: @SUM($G237..$G$237)
Extinction:I237: @EXP(-H237)
Extinction:J237: +I237^2

```

The following lines set up a search criteria and locate the extinction value for the altitude of interest (entered on the Results page).

```

Extinction:A241: 'Search Criteria
Extinction:C241: 'Result
Extinction:A242: 'Altitude
Extinction:C242: @EXP(-@DSUM(EXTINCTDAT,6,A242..A243))
Extinction:A243: +ALTITUDE>($ALT/1000)
Extinction:C245: 'This page searches the extinction database to find the alti-
tudes that are greater
Extinction:C246: 'than the target altitude. The values of extinction for the
path length through each
Extinction:C247: '0.1 km altitude band up to 20 km are summed. The value
obtained is the value of
Extinction:C248: ' (alpha*path length) which is used to calculate the one way
extinction through
Extinction:C249: 'the atmosphere.

```

4.8 Coherence length

The following code lists the contents of the cells on the page CoherenceL. The user sees a plot of the WPL-37 C_n^2 profile and a plot of the transverse coherence length as a function of altitude from the earth's surface. Column A contains the altitude, column B the nadir angle at that altitude, column C the range from the satellite to that altitude and column D the path length through an altitude increment. Column E calculates the refractive index structure function, C_n^2 at the altitude and columns F and G calculate the transverse coherence length.

```
CoherenceL:A36: `Altitude1
CoherenceL:B36: `Nadalt2
CoherenceL:C36: `range2
CoherenceL:D36: `path2
CoherenceL:E36: `Cn2
CoherenceL:F36: `multiplier
CoherenceL:A37: 0
CoherenceL:B37: @DEGREES(@ASIN((ORBH*10^3+RE)*@SIN(@RADIANS(NADIR)))/(RE+ALTITUDE1*1000)))
CoherenceL:C37: @SQRT(($ORBH*10^3+$RE)^2+($RE+ALTITUDE1*1000)^2-(2*$ORBH*10^3+2*$RE)*($RE+ALTITUDE1*1000)*@COS(@RADIANS(NADALT2-$NADIR)))/1000
CoherenceL:D37: 0
CoherenceL:E37: @IF(ALTITUDE1>20,0,@IF(ALTITUDE1<0.01,7.36*10^(-14),@IF(ALTITUDE1<3,1.59*10^(-12)*(ALTITUDE1*1000)^(-4/3),3.66*10^(-17))))
CoherenceL:F37: @IF(RANGE2>$R,0,PATH2*10^3*CN2*(1-RANGE2/$R)^(5/3))
CoherenceL:G37: ($HCOHERENCE*(2*@PI/($LAMBDA*10^(-6)))^2*@SUM(F37..$F$237))^(3/5)
CoherenceL:A38: 0.1
CoherenceL:B38: @DEGREES(@ASIN((ORBH*10^3+RE)*@SIN(@RADIANS(NADIR)))/(RE+$A38*1000)))
CoherenceL:C38: @SQRT(($ORBH*10^3+$RE)^2+($RE+$A38*1000)^2-(2*$ORBH*10^3+2*$RE)*($RE+$A38*1000)*@COS(@RADIANS($B38-$NADIR)))/1000
CoherenceL:D38: +RANGE2-$C38
CoherenceL:E38: @IF($A38>20,0,@IF($A38<0.01,7.36*10^(-14),@IF($A38<3,1.59*10^(-12)*($A38*1000)^(-4/3),3.66*10^(-17))))
CoherenceL:F38: @IF($C38>$R,0,$D38*10^3*$E38*(1-$C38/$R)^(5/3))
CoherenceL:G38: ($HCOHERENCE*(2*@PI/($LAMBDA*10^(-6)))^2*@SUM(F38..$F$237))^(3/5)
CoherenceL:A39: 0.2
CoherenceL:B39: @DEGREES(@ASIN((ORBH*10^3+RE)*@SIN(@RADIANS(NADIR)))/(RE+$A39*1000)))
CoherenceL:C39: @SQRT(($ORBH*10^3+$RE)^2+($RE+$A39*1000)^2-(2*$ORBH*10^3+2*$RE)*($RE+$A39*1000)*@COS(@RADIANS($B39-$NADIR)))/1000
CoherenceL:D39: +$C38-$C39
CoherenceL:E39: @IF($A39>20,0,@IF($A39<0.01,7.36*10^(-14),@IF($A39<3,1.59*10^(-12)*($A39*1000)^(-4/3),3.66*10^(-17))))
CoherenceL:F39: @IF($C39>$R,0,$D39*10^3*$E39*(1-$C39/$R)^(5/3))
CoherenceL:G39: ($HCOHERENCE*(2*@PI/($LAMBDA*10^(-6)))^2*@SUM(F39..$F$237))^(3/5)
```

A39 - G39 are repeated (with suitable increments) until:-

```
CoherenceL:A236: 19.9
CoherenceL:B236: @DEGREES(@ASIN((ORBH*10^3+RE)*@SIN(@RADIANS(NADIR)))/(RE+$A236*1000)))
CoherenceL:C236: @SQRT(($ORBH*10^3+$RE)^2+($RE+$A236*1000)^2-(2*$ORBH*10^3+2*$RE)*($RE+$A236*1000)*@COS(@RADIANS($B236-$NADIR)))/1000
CoherenceL:D236: +$C235-$C236
CoherenceL:E236: @IF($A236>20,0,@IF($A236<0.01,7.36*10^(-14),@IF($A236<3,1.59*10^(-12)*($A236*1000)^(-4/3),3.66*10^(-17))))
CoherenceL:F236: @IF($C236>$R,0,$D236*10^3*$E236*(1-$C236/$R)^(5/3))
```

```

CoherenceL:G236: ($HCOHERENCE*(2*@PI/($LAMBDA*10^(-6)))^2*
@SUM(F236..$F$237))^( -3/5)
CoherenceL:A237: 20
CoherenceL:B237: @DEGREES(@ASIN((ORBH*10^3+RE)*@SIN(@RADIANS(NADIR)) /
(RE+$A237*1000)))
CoherenceL:C237: @SQRT((($ORBH*10^3+$RE)^2+($RE+$A237*1000)^2-(2*$ORBH*10^3+
2*$RE)*($RE+$A237*1000)*@COS(@RADIANS($B237-$NADIR)))/1000
CoherenceL:D237: +$C236-$C237
CoherenceL:E237: @IF($A237>20,0,@IF($A237<0.01,7.36*10^(-14),
@IF($A237<3,1.59*10^-12*($A237*1000)^(-4/3),3.66*10^(-17))))
CoherenceL:F237: @IF($C237>$R,0,$D237*10^3*$E237*(1-$C237/$R)^(5/3))
CoherenceL:G237: ($HCOHERENCE*(2*@PI/($LAMBDA*10^(-6)))^2*
@SUM(F237..$F$237))^( -3/5)

```

The following lines set up a search criteria table and determine the refractive structure function at the altitude of interest given on the Results page.

```

CoherenceL:A239: `Search Criteria
CoherenceL:A240: `Altitude1
CoherenceL:C240: `Result
CoherenceL:A241: +ALTITUDE1>=$ALT/1000
CoherenceL:C241: ($HCOHERENCE*(2*@PI/($LAMBDA*10^(-6)))^2*@DSUM(WPL37-
DAT,5,A240..A241))^( -3/5)

```

4.9 Alignment

The following code lists the contents of the Alignment page. The user sees a plot of loss due to misalignment. Columns A and B contain a parameterised misalignment loss curve. Column B contains the misalignment loss as a function of the parameter, $\alpha D (\pi/\lambda)$ where α is the misalignment angle between the signal and BPLO, D is the optical beam diameter and λ is the lidar operating wavelength. Cells D37 - E44 contain a search table to find the two values of $\alpha D (\pi/\lambda)$ which straddle the misalignment angle given on the Instrument page. A linear interpolation between these two values is then performed to obtain the misalignment loss. Columns L and M contain the misalignment loss (column M) as a function of angle (column L) for the wavelength given on the Instrument page. These are the values plotted in the graph shown on this page.

```

Alignment:A36: `param
Alignment:B36: `eta_align
Alignment:L36: `deltaangl
Alignment:M36: `Loss
Alignment:A37: 0
Alignment:B37: 1
Alignment:D37: `Search Criteria
Alignment:L37: +PARAM*$LAMBDA/(@PI*$D)
Alignment:M37: 1-ETA_ALIGN
Alignment:A38: 0.1
Alignment:B38: 0.9987
Alignment:D38: ^Lower Limit
Alignment:E38: ^Upper limit
Alignment:G38: `XY Data Pairs
Alignment:L38: +A38*$LAMBDA/(@PI*$D)
Alignment:M38: 1-B38
Alignment:A39: 0.2
Alignment:B39: 0.9951
Alignment:D39: ^param
Alignment:E39: ^param
Alignment:G39: ^Xlower

```

```

Alignment:H39: ^Xupper
Alignment:I39: ^Ylower
Alignment:J39: ^Yupper
Alignment:L39: +A39*$LAMBDA/(@PI*$D)
Alignment:M39: 1-B39
Alignment:A40: 0.3
Alignment:B40: 0.9892
Alignment:D40: @ABS(PARAM-DUMMY1)<0.1#AND#PARAM<=DUMMY1
Alignment:E40: +PARAM>DUMMY1
Alignment:G40: @VLOOKUP(DUMMY1,ALIGNDAT,0)
Alignment:H40: @DMIN(ALIGNDAT,0,E39..E40)
Alignment:I40: @VLOOKUP(DUMMY1,ALIGNDAT,1)
Alignment:J40: @DMAX(ALIGNDAT,1,E39..E40)
Alignment:L40: +A40*$LAMBDA/(@PI*$D)
Alignment:M40: 1-B40
Alignment:A41: 0.4
Alignment:B41: 0.9812
Alignment:L41: +A41*$LAMBDA/(@PI*$D)
Alignment:M41: 1-B41
Alignment:A42: 0.5
Alignment:B42: 0.9708
Alignment:L42: +A42*$LAMBDA/(@PI*$D)
Alignment:M42: 1-B42
Alignment:A43: 0.6
Alignment:B43: 0.9583
Alignment:D43: "Search value (X) =
Alignment:E43: @ABS(ALIGN_ANGLE)*D*@PI/LAMBDA
Alignment:L43: +A43*$LAMBDA/(@PI*$D)
Alignment:M43: 1-B43
Alignment:A44: 0.7
Alignment:B44: 0.9436
Alignment:D44: "Solution (Y) =
Alignment:E44: @IF(DUMMY1=0,1,@IF(G40=H40,I40,+I40+(J40-I40)/(H40-
G40)*(DUMMY1-G40)))
Alignment:L44: +A44*$LAMBDA/(@PI*$D)
Alignment:M44: 1-B44
Alignment:A45: 0.8
Alignment:B45: 0.927
Alignment:L45: +A45*$LAMBDA/(@PI*$D)
Alignment:M45: 1-B45
Alignment:A46: 0.9
Alignment:B46: 0.9084
Alignment:L46: +A46*$LAMBDA/(@PI*$D)
Alignment:M46: 1-B46
Alignment:A47: 1
Alignment:B47: 0.8881
Alignment:D47: "This page searches the misalignment database to find the val-
ues that straddle
Alignment:L47: +A47*$LAMBDA/(@PI*$D)
Alignment:M47: 1-B47
Alignment:A48: 1.1
Alignment:B48: 0.8661
Alignment:D48: "the angular misalignment. A linear interpolation is then used
between these two
Alignment:L48: +A48*$LAMBDA/(@PI*$D)
Alignment:M48: 1-B48
Alignment:A49: 1.2
Alignment:B49: 0.8427
Alignment:D49: "points to determine the misalignment loss. The use of a linear
interpolation
Alignment:L49: +A49*$LAMBDA/(@PI*$D)
Alignment:M49: 1-B49
Alignment:A50: 1.3
Alignment:B50: 0.8179

```



```

Alignment:D50: 'introduces an error in the misalignment loss in the third decimal place this is
Alignment:L50: +A50*$LAMBDA/(@PI*$D)
Alignment:M50: 1-B50
Alignment:A51: 1.4
Alignment:B51: 0.7919
Alignment:D51: 'insignificant.
Alignment:L51: +A51*$LAMBDA/(@PI*$D)
Alignment:M51: 1-B51

```

The formulae in columns A,B,L and M are repeated until the data for the plot (columns L and M) are completed:-

```

Alignment:A156: 19.5
Alignment:B156: 0.00023224357861854
Alignment:L156: +A156*$LAMBDA/(@PI*$D)
Alignment:M156: 1-B156
Alignment:A157: 20
Alignment:B157: 0.0002147988979521
Alignment:L157: +A157*$LAMBDA/(@PI*$D)
Alignment:M157: 1-B157

```

The remaining rows then contain the rest of the misalignment look-up table until:-

```

Alignment:A172: 95
Alignment:B172: 1.95731733773E-06
Alignment:A173: 100
Alignment:B173: 1.67746225269E-06

```

4.10 Performance

The Perf page contains two plots, one of the wideband and narrowband SNR as a function of backscatter and one of the velocity error and probability of correct detection as a function of backscatter. The SNR plot contains a button which causes these graphs to be updated. The data for these plots is generated by the macro given in and is placed in cells A36 E59. Column A contains the backscatter value, B/C the wideband and narrowband SNR respectively and D and E contain the probability of a good estimate and the velocity error respectively.

Unlike the other plots which update themselves automatically when one of the relevant lidar parameters changes, these plots only update when the user clicks on the "Update Graphs" button. This will be discussed later.

This is the last page of direct relevance to the casual user - the remaining pages contain coding and although currently visible to the user they could be made invisible to prevent accidental alteration.

4.11 Constants

The following code lists the contents of the cells on the Constants page:-

```

Constants:A2: `h
Constants:B2: 662.60755*10^-36
Constants:C2: `J/s
Constants:A3: `c
Constants:B3: 299792458
Constants:C3: `m/s
Constants:A4: `re
Constants:B4: 6371315
Constants:C4: `m
Constants:A5: `me
Constants:B5: 5.979*10^24
Constants:C5: `kg
Constants:A6: `te
Constants:B6: 8.639988*10^4
Constants:C6: `sec
Constants:A7: `G
Constants:B7: 6.67259*10^-11
Constants:A8: `hcoherence
Constants:B8: 2.914383
Constants:A9: `1/pulse lngth
Constants:B9: 0.1874/TAU
Constants:C9: `MHz

```

4.12 Maximum liklihood estimator

This page contains a look-up table for the maximum liklihood estimator. The table is shown below together with the column and row assignments.

	B	C	D	E	F	G	H	I	J	K
1	Omega	M	b0	alpha	gamma	chi	g0	epsilon	delta	mu
2	3	20	4.6308	1.1923	1.2535	0.9145	6.2318	1.3798	0.5307	0.1462
3	3	25	6.6127	1.1843	1.573	0.887	4.3866	2.2939	0.2345	0.1082
4	3	30	9.6148	1.18	2.0453	0.9001	3.5357	3.1954	0.1401	0.0807
5	3	35	13.067	1.1495	2.5687	0.8758	4.2848	2.5322	0.2026	0.1
6	3	40	14.003	1.1862	2.7099	0.8854	3.5066	4.0879	0.1054	0.0761
7	6.7	20	0.2318	4.0951	0.0196	0.2138	17.454	1.1469	0.8738	0.4349
8	6.7	25	0.7783	5.6302	0.0499	0.5362	19.252	0.9637	1.2103	0.3021
9	6.7	30	2.2702	1.5914	0.4216	0.7402	12.063	1.1882	0.8432	0.2037
10	6.7	35	5.7615	1.1484	1.1356	0.8928	9.3993	1.2744	0.708	0.1468
11	6.7	40	9.832	1.0981	1.8154	0.9536	7.7512	1.4531	0.544	0.1122

4.13 Lists

This page contains small look-up tables used by the program. The tables are shown below, together with their row/column assignments. The first table is a list of wavelengths for which there are entries in the extinction database spreadsheet, ATMOS.WB1. This table appears as the pick list in the laser wavelength entry box.

	A
1	2.012552
2	2.021842
3	2.065479
4	2.091282
5	9.1145187
6	9.21969
7	9.249946
8	10.591043

The following table lists the available receiver geometries and their beam truncation factors.

	C	D	E	F	G
1	Geometry	Tt	etah	gammar	gammat
2	Wang	0.955	0.42	0.802	0.802
3	Matched Rye	0.929	0.457	0.87	0.87
4	Unmatched Rye	0.951	0.461	1.186	0.815

This small table is used in the receiver selection box to choose between complex and real receiver geometries (this affects the signal processing).

	I
1	Complex
2	Real

The next table lists the available scanning options and is used by the scanner input dialog.

	J
1	Dual-look
2	Conical
3	Wedge

4.14 Macros

The following table is a coded macro to calculate and plot the performance plots (Section 4.10). It is executed when the user clicks on the "Update Graphs" button on the SNR plot. Column A contains variable names and labels, column B contains the actual coding or the variable contents and column J contains comments on the macro steps.

	A	B	J
2	THIS MACRO RECALCULATES THE INSTRUMENT PERFORMANCE AS A FUNCTION OF BACKSCATTER		
3	AND UPDATES THE PERFORMANCE GRAPHS SO THAT ONLY PERFORMANCE FOR VALUES OF		
4	PROBABILITY > min_prob ARE PLOTTED. THIS IS BECAUSE THE VELOCITY ESTIMATION THEORY IS		
5	UNCERTAIN FOR PROBABILITIES LESS THAN THIS. IN PRACTICE IT IS UNLIKELY A LIDAR OF SUCH POOR		
6	SINGLE SHOT PERFORMANCE WOULD BE BUILT!		
7			
8	save_beta	1E-06	
9	beta_count	24	
10	min_beta_point	50	
11	min_prob	0.2	
12			
13	perform_calc	{ EDITGOTO perform:A1 } { LET \$save_beta, \$BETA }	Store beta value
14		{ FOR beta_count,0,23,1,beta_calc }	Repetitive calculation loop, increments beta value pointer
15		{ LET \$BETA,\$save_beta }	Restore beta to original value

	A	B	J
16		{WINDOWSOFF}{GraphEdit SNR}	Turn window updating off and edit the SNR graph
17		{SERIES.Data_Range 1,+"Perform:B"&@-STRING(min_beta_point,0)&"..B59"}	Change graph series to match new performance
18		{SERIES.Data_Range 2,+"Perform:C"&@-STRING(min_beta_point,0)&"..C59"}	Only performance for values of probability > 0.2 are plotted
19		{SERIES.Data_Range "XAxisLabelSeries",+"Perform:A"&@STRING(min_beta_point,0)&"..A59"}	
20		{Series.Go}{WindowClose}	Instigate graph changes and close edit window
21		{GraphEdit Vel_error}	Edit velocity error/probability graph
22		{SERIES.Data_Range 1,+"Perform:-E"&@STRING(min_beta_point,0)&"..E59"}	Change graph series to match new performance
23		{SERIES.Data_Range 2,+"Perform:D"&@-STRING(min_beta_point,0)&"..D59"}	Only performance values for probability > 0.2 are plotted
24		{SERIES.Data_Range "XAxisLabelSeries",+"Perform:A"&@STRING(min_beta_point,0)&"..A59"}	
25		{Series.Go}{WindowClose}	Instigate graph changes and close edit window
26			
27	beta_calc	{Let \$BETA,@INDEX(performance,0,beta_count)}	Set beta to value in performance table
28		{CALC}	Calculate performance
29		{Let +"perform:B"&@STRING(beta_count+36,0),snr_wide}	Store wideband SNR in performance table
30		{LET +"perform:C"&@STRING(beta_count+36,0),snr_narrow}	Store narrow band SNR in performance table
31		{LET +"perform:D"&@STRING(beta_count+36,0),pgood}	Store probability of good estimate in performance table
32		{LET +"perform:E"&@STRING(beta_count+36,0),sigmav_i}	Store velocity error in performance table
33		{IF pgood<min_prob}{LET min_beta_point,(beta_count+36)}	If probability is < 0.2 increment minimum beta pointer.

4.15 Other pages

The spreadsheet also contains two other pages - Messages and Block_Names. The Messages page will contain help messages which are accessible to the user (not currently implimented) whilst the Block_Names page contains a tabulation of the variable names assigned to cell locations. This page is not required for operation of the program but is included to assist in the further development of the program.

5.0 Appendix D - ANSI Z136.1-1992 Eye Safety Calculation

5.1 Program structure

Program EYES92 - main routine, allows user to select the MPE (Maximum Permissible Exposure) as :-

- a function of wavelength for a fixed pulse length or
- a function of pulse length for a fixed wavelength or
- a function of velocity resolution over a wavelength range (approximation).

The program saves the results to the data file mpevsl.dat (mpe vs wavelength) or mpevst.dat (mpe vs. pulse length). The output is in two columns, the first contains the variable (pulse length (s) or wavelength (μm) and the second contains the MPE (J/cm^2).

Function MPE92(LB,T) - is the function that calculates the MPE for a given wavelength, LB in microns and a given pulse length, T in seconds. Called by the main program.

Subroutine CLRSCRN(I) - is a utility subroutine that scrolls the output screen by I lines. Called by the main program.

5.2 Program code

5.2.1 Program EYES92

```
PROGRAM EYES92
C
  IMPLICIT NONE
  REAL*4 RESL,MIN,MAX,STEP,VAL,RESULT,LB,TP,MPE92,T
  INTEGER*2 OPTION
  CHARACTER*11 FILNAM
C
  CALL CLRSCRN(40)
  WRITE(*,*) '  1992 ANSI STANDARD EYE SAFETY CALCULATIONS'
  WRITE(*,*) '          Gary D. Spiers'
  WRITE(*,*) '      Center for Applied Optics'
  WRITE(*,*) '  University of Alabama in Huntsville'
  WRITE(*,*) '          Huntsville'
  WRITE(*,*) '          AL 35899'
  WRITE(*,*) '      (205) 895 6030 ext. 448'
  WRITE(*,*)
  WRITE(*,*) 'This program calculates the maximum permissible'
  WRITE(*,*) 'exposure (MPE) in  $\text{J}/\text{cm}^2$  for direct ocular exp-'
  WRITE(*,*) 'osure, intrabeam viewing to a laser beam. The '
  WRITE(*,*) 'valid wavelength range is 0.4-1000 microns and'
  WRITE(*,*) 'the valid pulse durations (half amplitude po-'
  WRITE(*,*) 'ints) are 1ns to 3000s. Pulses shorter than 1ns'
  WRITE(*,*) 'are treated as 1ns pulses at present due to '
  WRITE(*,*) 'inadequate safety data. All calculations are '
  WRITE(*,*) 'based on the ANSI Standard Z136.1-1992.'
  WRITE(*,*)
  PAUSE 'Type the return key to continue'
```

```

CALL CLRSCRN(40)
100  WRITE(*,*)
    WRITE(*,*) 'Three options are available:--'
    WRITE(*,*)
    WRITE(*,*) '1) MPE as a function of wavelength for a '
    WRITE(*,*) '    fixed pulse length.'
    WRITE(*,*) '    OR'
    WRITE(*,*) '2) MPE as a function of pulse length for a '
    WRITE(*,*) '    fixed wavelength.'
    WRITE(*,*) '    OR'
    WRITE(*,*) '3) MPE as a function of velocity resolution'
    WRITE(*,*) '    over a wavelength range.'
    WRITE(*,*)
    WRITE(*,*) 'ENTER OPTION NUMBER:'
    READ(*,*) OPTION
    WRITE(*,*)
    IF ((OPTION .NE.1) .AND. (OPTION.NE.2) .AND. (OPTION.NE.3)) THEN
        WRITE(*,*) 'Please use a valid option number!!!!'
        GOTO 100
    ELSEIF (OPTION.EQ.1) THEN
        WRITE(*,*) 'ENTER PULSE LENGTH (MICROSECONDS):--'
        READ(*,*) TP
        T=TP*0.000001
        IF ( T .LT. 1E-9) THEN
            WRITE(*,*)
            WRITE(*,*) 'Pulselength set to 1ns.'
            T =1E-9
        ENDIF
        IF (T .GT. 3000) THEN
            WRITE(*,*)
            WRITE(*,*) 'Pulse length set to 3000s.'
            T =3000
        ENDIF
    ELSEIF (OPTION .EQ. 2) THEN
130  WRITE(*,*) 'ENTER WAVELENGTH (MICRONS) :--'
        READ(*,*) LB
        IF ((LB .LT. 0.4) .OR. (LB .GT. 1000)) THEN
            WRITE(*,*)
            WRITE(*,*) 'The wavelength must be in the range
@ 0.4-1000 microns.'
            GOTO 130
        ENDIF
140  WRITE(*,*) 'ENTER THE MINIMUM AND MAXIMUM PULSE'
        WRITE(*,*) 'LENGTHS OF INTEREST (microseconds) :--'
        READ(*,*) MIN,MAX
        IF((MIN.LT.0.001) .OR. (MAX.GT.3000) .OR. (MAX.LT.MIN)) THEN
            WRITE(*,*) ' Please provide valid values in the range'
            WRITE(*,*) ' 0.001 to 3000 microseconds!'
            GOTO 140
        ENDIF
    ELSEIF (OPTION .EQ. 3) THEN
150  WRITE(*,*) 'ENTER VELOCITY RESOLUTION (m/s) :--'
        READ(*,*) RESL
        IF (RESL .LE. 0.0) THEN
            WRITE(*,*)
            WRITE(*,*) 'The velocity resolution must be a
@ positive number.'
            GOTO 150
        ENDIF
    ENDIF
    IF (OPTION .NE. 2) THEN
        WRITE(*,*)
        WRITE(*,*) 'Now set up wavelength range of interest.'
        WRITE(*,*) 'Wavelength increment is 5nm.'
200  WRITE(*,*)

```



```

WRITE(*,*) 'ENTER MINIMUM AND MAXIMUM WAVELENGTH'
WRITE(*,*) '(MICRONS):-'
READ(*,*) MIN,MAX
WRITE(*,*)
IF((MIN.LT.0.4) .OR. (MAX.GT.1000) .OR. (MAX.LT.MIN)) THEN
  WRITE(*,*) ' Please provide valid values in the range'
  WRITE(*,*) ' 0.4 to 1000 microns!!!!'
  GOTO 200
ENDIF
WRITE(*,*) 'The data will be written to the file mpevsl.dat.'
FILNAM='mpevsl.dat'
ELSEIF (OPTION .EQ. 2) THEN
  WRITE(*,*) 'The data will be written to the file mpevst.dat.'
  WRITE(*,*) 'The pulse length increment is 5 ns.'
  FILNAM='mpevst.dat'
ENDIF
OPEN(1,FILE=FILNAM)
STEP=0.005
DO 300 VAL = MIN, MAX, STEP
  IF (OPTION .EQ. 1) THEN
    LB=VAL
  ELSEIF (OPTION .EQ. 2) THEN
    T=VAL*0.000001
  ELSEIF (OPTION .EQ. 3) THEN
    LB=VAL
    T=LB*1E-6/(2*RESL)
  ENDIF
  RESULT=MPE92(LB,T)
  IF (OPTION .NE. 2) THEN
    WRITE(1,*) LB,RESULT
  ELSEIF (OPTION .EQ. 2) THEN
    WRITE (1,*) T,RESULT
  ENDIF
300 CONTINUE
STOP
END

```

5.2.2 Function MPE92

```

REAL*4 FUNCTION MPE92(LB,T)
REAL*4 CA,CB,T1,LB,CC,T
C
IF ((LB .GE. 0.4) .AND. (LB .LT. 0.7)) THEN
  CA=1
  ELSEIF ((LB .GE. 0.7) .AND. (LB .LT. 1.050)) THEN
    CA=10**(2.0*(LB-0.7))
  ELSEIF ((LB .GE. 1.050) .AND. (LB .LT. 1.4)) THEN
    CA=5
  ENDIF
C
IF ((LB .GE. 0.4) .AND. (LB .LT. 0.55)) THEN
  CB=1
  ELSEIF ((LB .GE. 0.55) .AND. (LB .LE. 0.7)) THEN
    CB=10**(15*(LB-0.55))
  ENDIF
C
IF ((LB .GT. 1.05) .AND. (LB .LE. 1.15)) THEN
  CC=1.0
  ELSEIF ((LB .GT. 1.15) .AND. (LB .LE. 1.2)) THEN
    CC=10**(18*(LB-1.15))
  ELSEIF ((LB .GT. 1.2) .AND. (LB .LE. 1.4)) THEN

```

```

      CC=8
    ENDIF
C
    IF ((LB .GE. 0.55) .AND. (LB .LE. 0.7)) THEN
      T1=10*10**(20*(LB-0.55))
    ENDIF
C
    IF (LB .LE. 0.7) THEN
      IF (T .LE. 1.8E-5) THEN
        MPE92=5E-7
      ELSEIF ((T .GT. 1.8E-5) .AND. (T .LT. 10)) THEN
        MPE92=1.8*T**0.75*1E-3
      ELSEIF ((LB .LT. 0.55) .AND. (T .GT. 10) .AND. (T
@ .LE. 1E4)) THEN
        MPE92=0.01
      ELSEIF ((LB .GT. 0.55) .AND. (T .GT. 10) .AND. (T .LE. T1)
@) THEN
        MPE92=1.8*T**0.75*1E-3
      ELSEIF ((LB .GT. 0.55) .AND. (T .GT. T1) .AND. (T .LE. 1E
@4)) THEN
        MPE92=10*CB*0.001
      ELSEIF ((LB .GE. 0.4) .AND. (T .GT. 1E4) .AND. (T .LE. 3E
@4)) THEN
        MPE92=CB*1E-6
      ENDIF
    ELSEIF ((LB .GT. 0.7) .AND. (LB .LE. 1.05)) THEN
      IF (T .LE. 1.8*1E-5) THEN
        MPE92=5*CA*1E-7
      ELSEIF ((T .GT. 1.8*1E-5) .AND. (T .LE. 1E3)) THEN
        MPE92=1.8*CA*T**0.75*0.001
      ELSEIF ((T .GT. 1E3) .AND. (T .LE. 3E4)) THEN
        MPE92=320*CA*1E-6
      ENDIF
    ELSEIF ((LB .GT. 1.05) .AND. (LB .LE. 1.4)) THEN
      IF (T .LE. 5E-5) THEN
        MPE92=5*CC*1E-6
      ELSEIF ((T .GT. 5E-5) .AND. (T .LE. 1E3)) THEN
        MPE92=9*CC*T**0.75*0.001
      ELSEIF ((T .GT. 1E3) .AND. (T .LE. 3E4)) THEN
        MPE92= 1.6*CC*1E-3
      ENDIF
    ELSEIF ((LB .GT. 1.4) .AND. (LB .LE. 1.5)) THEN
      IF (T .LE. 1E-3) THEN
        MPE92=0.1
      ELSEIF ((T .GT. 1E-3) .AND. (T .LE. 10)) THEN
        MPE92=0.56*T**0.25
      ELSEIF ((T .GT. 10) .AND. (T .LE. 3E4)) THEN
        MPE92=0.1
      ENDIF
    ELSEIF ((LB .GT. 1.5) .AND. (LB .LE. 1.8)) THEN
      IF (T .LE. 10) THEN
        MPE92=1
      ELSEIF ((T .GT. 10) .AND. (T .LE. 3E4)) THEN
        MPE92=0.1
      ENDIF
    ELSEIF ((LB .GT. 1.8) .AND. (LB .LE. 2.6)) THEN
      IF (T .LE. 1E-3) THEN
        MPE92=0.1
      ELSEIF ((T .GT. 1E-3) .AND. (T .LE. 10)) THEN
        MPE92=0.56*T**0.25
      ELSEIF ((T .GT. 10) .AND. (T .LE. 3E4)) THEN
        MPE92=0.1
      ENDIF
    ELSEIF ((LB .GT. 2.6) .AND. (LB .LE. 1E3)) THEN
      IF (T .LE. 1E-7) THEN

```

```

MPE92=1E-2
ELSEIF ((T .GT. 1E-7) .AND. (T .LE. 10)) THEN
MPE92=0.56*T**0.25
ELSEIF((T .GT. 10) .AND. (T .LE. 3E4)) THEN
MPE92=0.1
ENDIF
ENDIF
RETURN
END

```

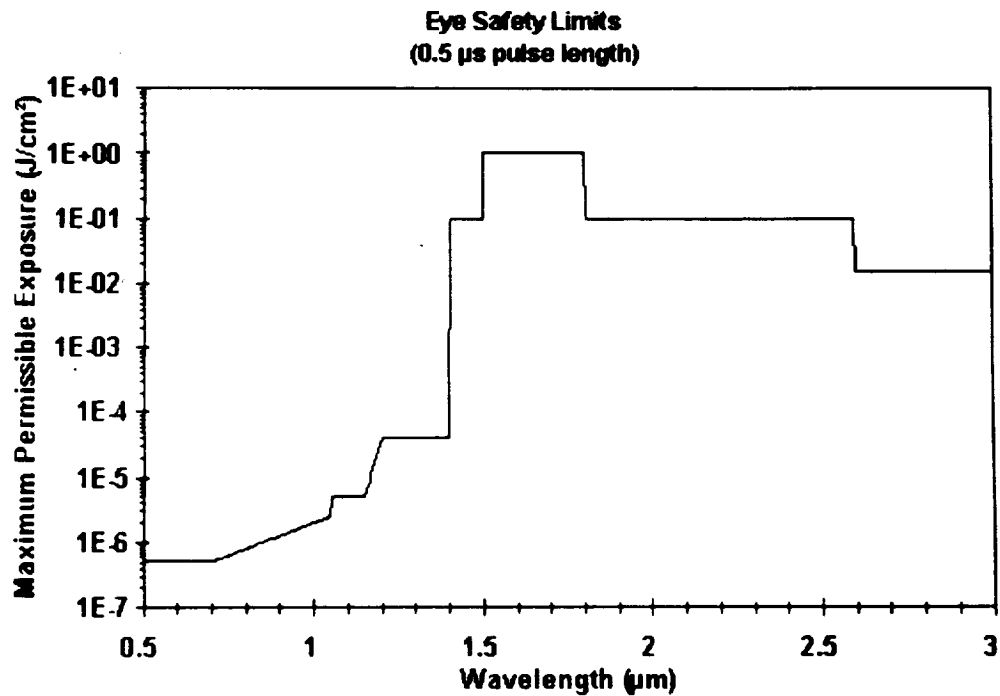
5.2.3 Subroutine CLRSCRN

```

SUBROUTINE CLRSCRN(I)
INTEGER J,I
DO 100 J=1,I,1
WRITE(*,*)
100 CONTINUE
RETURN
END

```

5.3 Sample plot of data



6.0 Appendix E - Eye Safety Analysis

The following paper was presented as Paper TuA6 at the 7th. Coherent Laser Radar Applications and Technology Conference, Paris, France, 19th-23rd July 1993.

Eye Safety Considerations For Selecting The Wavelength of a Space Based Coherent Doppler Wind Lidar

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Introduction

This paper derives an expression for the eye safety of a coherent doppler wind lidar starting from the signal to noise ratio (SNR) equation. The intensity at the eye of a potential observer and the proposed 1993 ANSI eye safety standard are folded in to produce an eye danger index.

Theory

The SNR from an aerosol target (subscript a) at range, R_a , from a lidar operating at a wavelength, λ , is given by:

$$\text{SNR}(\lambda) = \frac{\pi D_B^2 U_L \eta(\lambda) K_{ta}(\lambda) K_{ra}(\lambda) c \beta_a(\lambda) T_t(\lambda) T_r(\lambda)}{8 h \nu B(\lambda) R_a^2 \left[1 + \left(\frac{D_B}{2 \rho_{0a}(\lambda)} \right)^2 \right]} \quad (1)$$

where U_L is the laser pulse energy at the laser, $K_{ta}(\lambda)$ and $K_{ra}(\lambda)$ are the atmospheric transmission of the transmit and receive beams, c is the speed of light, $\beta_a(\lambda)$ is the atmospheric backscatter coefficient, $T_t(\lambda)$ and $T_r(\lambda)$ are the transmittance of the transmit and receive optics, h is Planck's constant, ν is the laser frequency, $B(\lambda)$ is the processing noise bandwidth and $\rho_{0a}(\lambda)$ is the transverse field coherence length. $\eta(\lambda)$ is the efficiency of the lidar which is given by:

$$\eta(\lambda) = \eta_s(\lambda) \eta_\alpha(\lambda) \eta_p(\lambda) \eta_q(\lambda) \eta_u(\lambda) \quad (2)$$

where $\eta_s(\lambda)$, $\eta_\alpha(\lambda)$, $\eta_p(\lambda)$, $\eta_q(\lambda)$ and $\eta_u(\lambda)$ are the lidar system, misalignment, polarisation, effective heterodyne quantum and unexplained loss efficiencies respectively. For a Gaussian beam

the $1/e^2$ intensity diameter of the transmitted beam, D_B , is optimised relative to the telescope physical diameter, D_T , when [1]:

$$D_B = 0.802 D_T \quad (3)$$

The processing noise bandwidth, $B(\lambda)$ is:

$$B(\lambda) = \frac{2V_s}{\lambda} \quad (4)$$

where V_s is the velocity search window.

The intensity, Q_e at the eye of an observer (subscript e) at a distance, R_e , from the lidar, including diffraction but assuming negligible spreading of the beam by refractive turbulence is given by:

$$Q_e(\lambda) = \frac{4\pi D_B^2 U_L K_{te}(\lambda) T_t(\lambda) M}{16R_e^2 \lambda^2 + \pi^2 D_B^4} \quad (5)$$

where $K_{te}(\lambda)$ is the atmospheric transmission to the observer and M is a factor to account for the transverse intensity distribution of the optical beam. For example, for a fixed pulse energy, the intensity on the axis of a Gaussian beam is twice that of a uniform beam with the same diameter and therefore $M=2$ for a Gaussian profile.

An eye danger index $X(\lambda)$ can be defined by:

$$X(\lambda) = \frac{Q_e(\lambda)}{Q_{mpe}(\lambda)} \quad (6)$$

where $Q_{mpe}(\lambda)$ is the proposed 1993 ANSI eye safety standard maximum permissible exposure (MPE) value shown in Figure (1a) for a $1\mu s$ pulse length. For values of $X(\lambda) > 1$ the lidar exceeds the ANSI specification. Combining Equations (1,2,4-6) gives:

$$X(\lambda) = \frac{16SNR(\lambda) hV_s MR_a^2 K_{te}(4\rho_{0a}^2(\lambda) + D_B^2)}{\eta(\lambda) K_{ra}(\lambda) K_{ta}(\lambda) T_r(\lambda) \lambda^2 \beta_a(\lambda) Q_{mpe}(\lambda) \rho_{0a}(\lambda)^2 (\pi^2 D_B^4 + 16\lambda^2 R_e^2)} \quad (7)$$

Figures (1b) and (1c) show the value of $X(\lambda)$ over the wavelength range 1-12 μm for a space based lidar and an earth based observer using the parameters listed in Table (1). The calculations assume a spherical earth, a lidar altitude of 525 km, a 45° nadir scan angle, an aerosol target at an altitude of 10 km and an observer on the ground. The minimum detectable SNR was taken as -13.2 dB, independent of wavelength. Both a λ^{-2} (Figure (1b)) and a λ^{-1} (Figure (1c)) dependence of backscatter on wavelength were used to represent typical values near 10 km altitude. The backscatter was anchored to a value of $5 \times 10^{-11} (m-sr)^{-1}$ at 9.11 μm , again a typical value for 10 km. A laser pulse length of 1 μs was assumed when determining the MPE values. For wavelengths shorter than 2.6 μm the MPE does not depend on pulse length for pulses of width 1 ns - 50 μs , and only a weak pulse length dependence exists for wavelengths longer than 2.6 μm . The transverse coherence length has a $\lambda^{6/5}$ dependence and was anchored to a value of 58 m at 9.11 μm . The wavelength dependent atmospheric transmission is not suited to a simple expression and a constant

value of 0.86 was assumed for the atmospheric transmission to the observer. Atmospheric extinction to the aerosol target was assumed to be negligible.

SNR(λ)	-13.2 dB
h	6.62607×10^{-34} Js
V_s	50 ms^{-1} or $\pm 25 \text{ ms}^{-1}$
$T_r(\lambda)$	0.95
M	2
$\beta_a(\lambda)$	$5 \times 10^{-11}/(\text{m-sr})$ @ 9.11 μm
$Q_{\text{mpe}}(\lambda)$	ANSI standard (Figure 1a)
R_a	754.2 km
R_e	775.9 km
D_T	1.5 m

$\eta_s(\lambda)$	0.46
$\eta_\alpha(\lambda)$	0.5
$\eta_p(\lambda)$	1
$\eta_q(\lambda)$	0.4
$\eta_u(\lambda)$	0.5
$K_{ra}(\lambda)$	1
$K_{ta}(\lambda)$	1
$K_{te}(\lambda)$	0.86
$\rho_{0a}(\lambda)$	58 m @ 9.11 μm

Table 1: Parameter values used to calculate Figures (1b) and (1c).

Discussion

We have combined the coherent lidar SNR equation with the ANSI eye safety standard to arrive at an expression for eye danger index. Equation (7) is valid for any location of a coherent Doppler lidar, aerosol target and human observer; however Figures (1b) and (1c) apply only to the specific space based configuration described in Table 1. For the space based configuration, the parameters in Equation (7) with the largest dynamic range are λ , $Q_{\text{mpe}}(\lambda)$ and $\beta(\lambda)$. Limitations of the existing calculations are the use of wavelength independent terms for misalignment loss, atmospheric transmission, SNR threshold, detector quantum efficiency and exponent for the backscatter wavelength dependence.

References

[1] B.J. Rye and R.G. Frehlich, Appl. Optics, 31, 2891 - 2899 (1992).

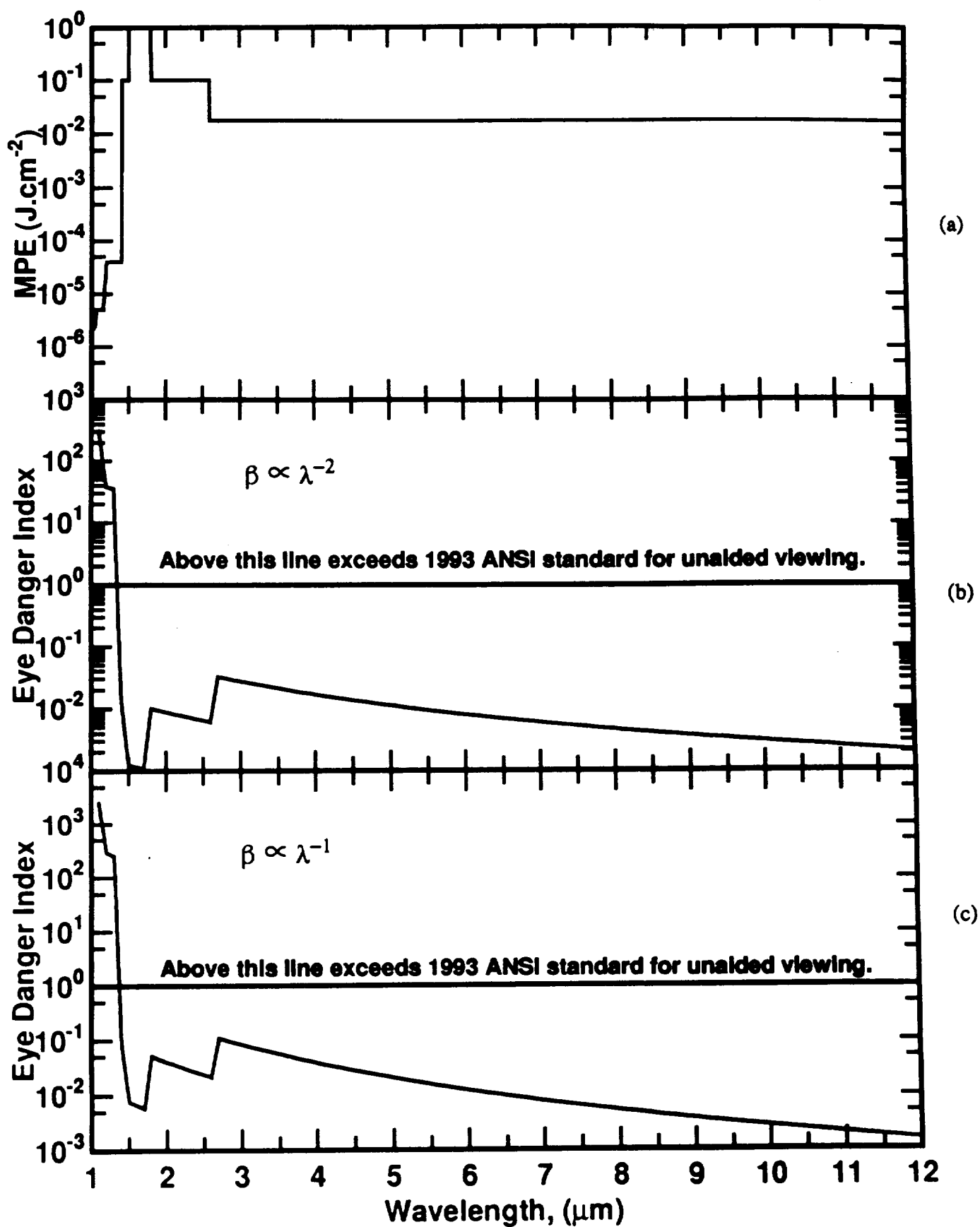


Figure 1a) The MPE for a $1 \mu\text{s}$ pulse. b) and c) The eye danger index for the two backscatter dependencies on wavelength discussed in the text.

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